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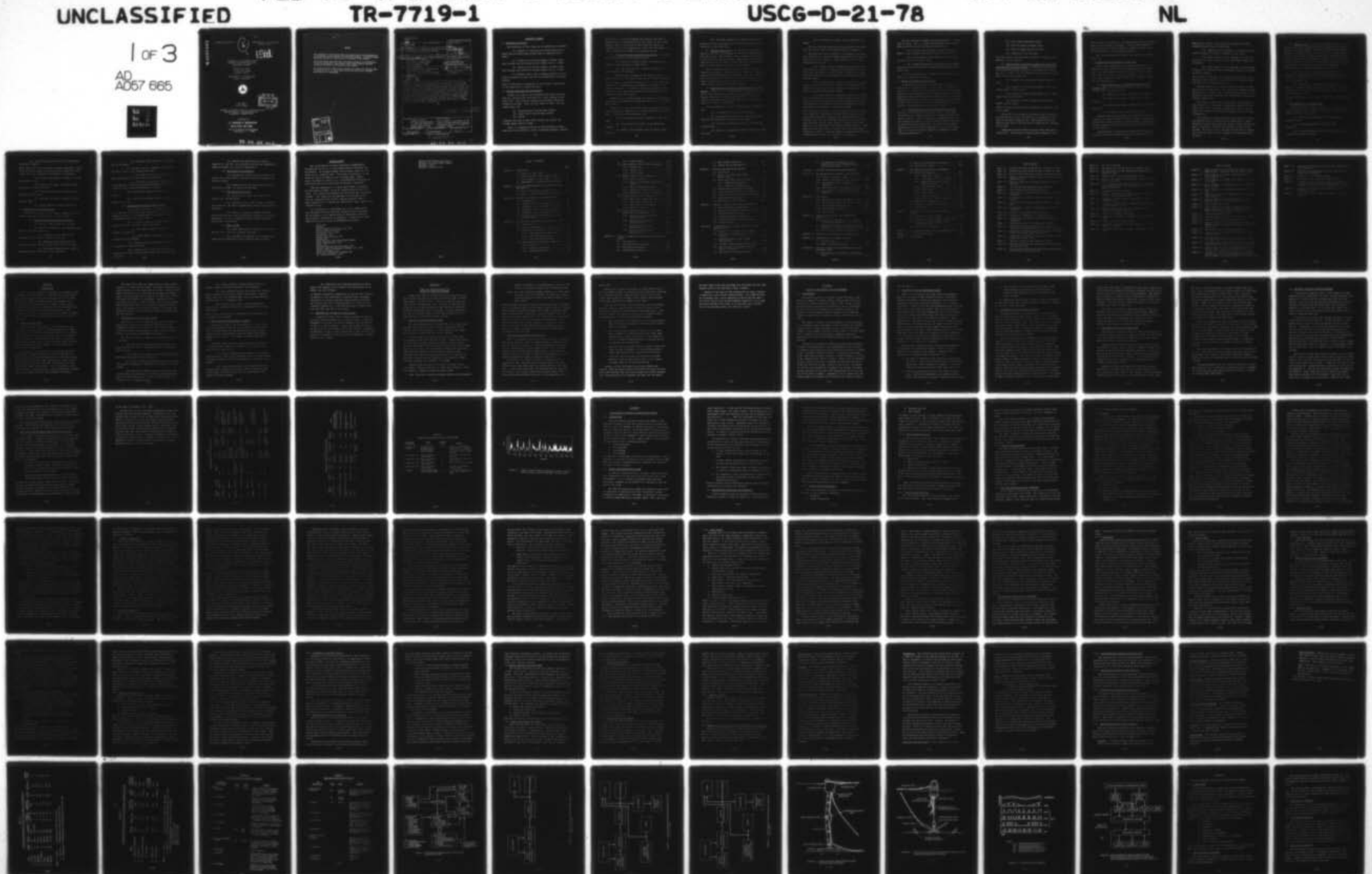

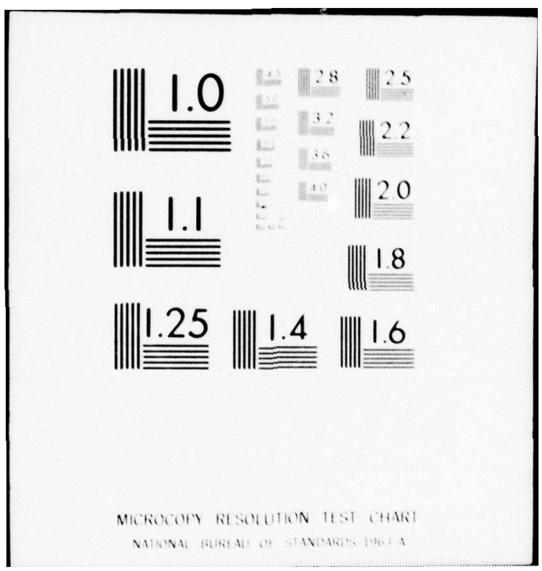
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EVALUATION OF DEEPWATER PORTS MOORING LOAD MONITORING AND PREDICTION SYSTEMS

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LAUREL, MARYLAND

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Final Report

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16. Abstract

This report describes a study of mooring load monitoring and prediction systems for deepwater ports. The study considers both the complete systems and the various components of each system. The primary purpose of the study is to define and critically compare all candidate monitoring and prediction systems that might be used at a U. S. deepwater port and to recommend what, if any, systems should be required at such ports. The study is primarily directed to oil import terminals using single point moorings of the CALM, SALM and tower types, but alongside moorings and LNG ports are considered briefly. Factors such as hawser properties, which affect allowable mooring loads, are also considered.

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EXECUTIVE SUMMARY

A. Objectives and Scope

The objectives of this study can be summarized as follows:

(1) Examine all existing and possible methods for monitoring and predicting mooring loads at deepwater ports (DWPs).

(2) Define and critically compare suitable candidate mooring load monitoring systems (MLMSs) for U. S. DWPs.

(3) Define and critically compare suitable candidate mooring load prediction systems (MLPSs) for U. S. DWPs.

(4) Examine areas, such as hawser properties, which affect allowable mooring loads and the probability of mooring failure.

Each of these areas is addressed in this study, is described in the report and is summarized below.

B. Review of Mooring Load Measurement

During this study it was determined that MLMs are available for, and have been installed at, a wide variety of port facilities. These include single point moorings (SPMs) and alongside moorings. There are many types of SPMs. The most common types are:

(1) Catenary Anchor Leg Moorings (CALMs)
(2) Single Anchor Leg Moorings (SALMs)
(3) Towers

Alongside moorings at DWPs could include sea islands and storage barges moored at SPMs.

The U. S. Deepwater Port Act of 1974 describes a deepwater port as an offshore, fixed or floating man-made structure

to be used as a port or terminal for loading, unloading or handling oil for transportation to any state. In this study, primary emphasis was placed on SPMs facilities which are ideally suited to oil importation. Ports for other purposes, such as importation of LNG, are considered briefly.

(1) Existing Mooring Load Monitoring Systems. Existing MLMs are generally of the following types:

(a) Systems installed at piers for making simultaneous load measurements in many lines.

(b) Systems installed on dedicated ships which visit specific SPM terminals.

(c) Systems installed on SPMs which telemeter hawser load data to the ship, ashore or to a control platform.

The last type is of primary interest for U. S. DWPs, but some requirements, capabilities and equipment are common to all three system types. In addition, operating experience with all three system types can be useful in determing how a MLMs can be used most effectively.

Figure 4-2 is a block diagram of a typical existing MLMs. It also is the recommended minimum MLMs for use at U. S. deep-water ports.

Table 3-1 is a listing of MLMs which have been installed on SPM terminals. Table 3-2 is a listing of MLMs on order for SPMs. Some pertinent observations are:

(a) Most systems have been installed on CALM type SPMs.

(b) Strain gaged load cells are the preferred sensors.

(c) Radio is the preferred type of signal transmission.

(d) Operating experience has generally been good. Relatively little experience has been obtained with systems installed on SALM type SPMs.

(2) Operating Experience. Discussions with terminal operators indicate that properly designed MLMSs work reliably and effectively. They provide a basis for decisions on when a ship can moor, when to terminate cargo transfer, and when a ship should leave the moor. At many facilities a ship cannot moor or remain moored if the MLMS is not working.

There is evidence that a MLMS can be used to increase terminal utilization. This is because a ship could stay moored longer when the mooring loads are known. Also, some terminals have found that with a MLMS the ship's rudder can be used to reduce yawing and the resultant peak loads. This has been found effective without using ship's power.

(3) Specification and Critical Comparison of MLMS Components. Figure 4-1 is a block diagram of a generalized MLMS. The load measurement, data handling, load warning and data display subsystems are defined and specified in Section 4. Different configurations and components are critically compared in Section 5 of the report.

Some pertinent notes on the load measurement subsystems are:

(a) It should be located on the SPM buoy.

(b) The preferred sensor is a strain gaged load cell and the shear pin is the best of this type.

(c) The sensor should be located at the buoy end of the hawser.

(d) Radio is the preferred signal transmission link for CALMs.

(e) An underwater acoustic link is preferred for SALMs.

The data handling subsystem presents no particular problems and can be composed of readily available components.

The MLMS must have an effective load warning subsystem, and experience has shown that human surveillance of data displays alone is not adequate. Some pertinent notes on the warning subsystem are:

(a) It will consist of warning devices (typically both aural and visual), a transmission link between the control center and ship, a suitable logic, software and hardware for activating devices and perhaps a means for deactivating warning signals.

(b) Warning devices should be installed at several locations (including the ship's bridge) and must unequivocally direct attention to the existence of a dangerous situation or a condition of imminent danger.

(c) Four conditions requiring issuance of a warning are: the detection of a hawser failure or MLMS failure, measurement of load exceeding an allowable maximum, prediction of load exceeding an allowable maximum and measurement of load reaching 80 to 90 percent of allowable maximum.

The first two conditions of item (c) require decisive action, i.e., immediate termination of cargo transfer operations and an immediate decision on whether the ship should leave the mooring. The last two conditions of item (c) act as a cue to port personnel and the ship's master to review load records, wind and wave conditions, and the ship's yawing motions. They may also carry out actions to reduce loads and alert cargo handling personnel. A warning system is required which clearly differentiates between the two types of situations.

The data display in present systems generally is a strip chart recorder. For U. S. DWPs the recommended data display subsystem will have the following characteristics:

(a) A strip chart recorder or oscilloscope and magnetic tape recorder will be used in the control room.

(b) A CRT terminal and/or digital meters should also be used in the control room.

(c) A small lightweight oscilloscope, for displaying recent load history, and/or digital meters will be used aboard ship.

It is not only possible to obtain a good MLMS for U. S. DWP use; it should be required.

C. Review of Mooring Load Prediction

A deepwater port mooring load prediction system (MLPS) will be used to predict future hawser loads. In addition it may be used to predict allowable hawser loads based on hawser condition, age, loading history or current details of loading. Any method for predicting mooring loads at a future time will probably be based on a prediction of the expected environment at that time, as well as a means for predicting the load as a function of environment and ship characteristics.

(1) Description of Mooring Load Prediction Methods. Mooring load prediction methods range from a simple human extrapolation to complex theoretical or highly developed empirical methods. Table 6-1 presents a characterization of five prediction methods listed in order of increasing period of applicability and complexity. The first method, human extrapolation, is the only known method in use at existing DWPs. It is based on human judgment and synthesis of the following information:

(a) Most recent peak hawser load.

(b) Rate of change of hawser loads.

(c) Rate of change of wind velocity.

(d) Yawing motion of the ship.

The other methods are described in detail in Section 6 and Appendix D of the report.

(2) Specification and Critical Comparison of Mooring Load Prediction Systems (MLPSs). A MLPS with an automated short-term extrapolation method is recommended for initial use at U. S. DWPs. This is primarily an empirical technique which uses the following data:

(a) Present wind speed, wave height and hawser load.

(b) Variation of item (a) parameters over a preceding period (say one hour).

(c) Predicted change in wind speed over a following period (say one hour).

(d) Empirical trends in hawser load with wave height and wind speed.

Computer programs using various extrapolation techniques can be developed.

The medium-term extrapolation methods would probably be an extension of a short-term method or an empirical method such as the EXXON energy method. Such medium-term methods would be used after a DWP has been in operation for some period of time.

Long-term prediction methods can be either empirical or theoretical. The accuracy of predictions decreases as the

term of prediction increases. At the present time only empirical methods have acceptable accuracy, but the time required to acquire needed data and the amount of computer storage reduce the attractiveness of such empirical methods.

The various mooring load prediction systems are ranked in Table 7-1.

D. Determination of Allowable Mooring Loads

Hawser elastic properties and breaking strength are a function of rope condition, age, loading history and loading rate. Allowable hawser load and warning load levels should take these factors into account. In addition, the condition of a ship's mooring fittings, if definable, should be factored into the warning level.

(1) Factors Which Limit Allowable Mooring Loads and Warning Levels. The following factors can limit allowable mooring loads and warning levels:

(a) Reduction of hawser strength due to damage.

(b) Reduction of hawser strength due to cyclic loading.

(c) Reduction of hawser strength due to high loading rates.

(d) Allowable ship mooring fitting loads.

Physical and chemical damage are the primary causes of reduction in hawser strength. Physical damage can often be determined by careful inspection of the hawser. Nevertheless, physical damage remains the primary cause of hawser failures at SPM terminals.

Repeated cyclic loading of the hawser will result in a decrease in hawser strength with age, as discussed in the

EXXON Phase I report. This decreased strength can affect allowable hawser load in several ways:

(a) Repeated cyclic loadings at a level well below static strength can result in failure at that level.

(b) After repeated cyclic loadings at a level insufficient to produce failure, static breaking strength will be reduced.

(c) After repeated cyclic loadings, total breaking energy will be reduced, reducing breaking strength for dynamic or shock loadings.

The behavior of synthetic ropes under cyclic loading is not well understood; however, some guidance can be obtained from available cyclic loading test data.

Maximum hawser loads usually occur as a result of large motions of the moored ship. These motions can produce sudden hawser snatch or impact loads. Existing MLMSs probably do not accurately indicate or display high loading rates and instantaneous maximum loads.

The extent to which high loading rates can precipitate hawser failures is not known. Experimental results for synthetic ropes up to three-inch circumference indicate that a significant reduction in breaking strength can occur at high loading rates.

The influence of ship mooring fitting strength on allowable mooring load is discussed in the EXXON Phase I report. Clearly the hawser load should not exceed a safe fitting load, which is defined as one-half the ultimate capacity of the fitting. The hawser and all mooring fittings must be compatible to ensure that the full strength of the mooring can be utilized.

(2) Warning Levels. As noted in report Section 4.4, it is proposed that the load warning system incorporate two distinct warning levels and signals. The first, would indicate the probability of occurrence of an excessive load in the near future, the need for extreme vigilance and the need for any available actions, such as rudder steering, to reduce loads. The second, would indicate the occurrence of an excessive load and the need for immediate termination of cargo transfer operations. It is proposed that these warning levels be set as follows:

(a) First Level: Measured load reaches 60 to 70 percent of allowable load, as described in report Section 8.4, or predicted load during the next 30 minutes reaches 80 percent of allowable load.

(b) Second Level: Measured load reaches 80 to 90 percent of allowable load, as described in report Section 8.4, or predicted load during the next 30 minutes reaches 100 percent of allowable load.

If only one warning level is used, it should be set at the first level.

E. Recommendations for Further Study

In the Exxon Phase I report (Flory, et al., 1977) four topics dealing with the strength of ropes are recommended for further reasearch. These are:

(1) Establish test procedures for large-diameter synthetic ropes.

(2) Develop large-diameter synthetic rope properties.

(3) Develop nondestructive means and practices for determining new-rope strength.

(4) Develop means and practices for determining used-rope strength.

These topics are still considered of great importance. Based on the research carried out in the present study, five additional areas are recommended for further investigation:

(a) Determine the dynamic strength of new and used synthetic rope.

(b) Consider the impact of unique features of LNG ports on MLMS and MLPS.

(c) Develop criteria for ship mooring and unmooring requirements.

(d) Determine the ambient acoustic environment for SPMs.

(e) Develop empirical prediction methods.

F. <u>Conclusions and Recommendations</u>

Based on the results of this study, a number of conclusions seem worthy of special note. These include:

(1) <u>Mooring Load Monitoring Systems (MLMS)</u>.

(a) All U. S. DWPs should have an MLMS.

(b) This MLMS should have the following capabilities and characteristics:

<u>1</u>. A display of load time history covering at least one hour should be provided.

<u>2</u>. Aural and visual warning devices should be provided at the control center and on the ship.

<u>3</u>. Voice radio communication should be provided between the control center and ship.

4. The load sensor should be at the buoy end of the hawser.

(c) The most critical component of the MLMS is the buoy control center transmission link.

1. For CALMs and towers a well designed radio link should be reliable and is recommended.

2. For SALMs an underwater acoustic link is recommended, but there are potential problems with signal corruption and a relay will probably be required.

(d) Overall MLMS accuracy should be five percent.

(e) Overall MLMS maximum frequency response should be 0.5 Hertz.

(2) Mooring Load Prediction System (MLPS)

(a) A long term MLPS is not required for a U. S. DWP, due to the short times required to terminate DWP operations, but it is recommended that an empirical short- or medium-term MLPS be used at a DWP.

(b) It seems feasible to develop empirical methods which have adequate accuracy and which:

1. Have modest computer hardware and software requirements.

2. Can be updated and improved as operational data are obtained.

(c) Careful processing of measured load data is required for empirical MLPSs.

(d) Long-term (six to 48 hour) MLPSs are not required and suitable predictional schemes will be difficult to develop.

(e) Methods for predicting wave heights, required for any MLMS, are available, but may have significant computer hardware and software requirements.

(3) Environmental Measurements

(a) Measurements of wind speed and direction, current speed and direction, and wave height are required for decision making.

(b) Weather predictions and a means for predicting wave heights are needed for any MLPS.

(4) DWP Operational Factors

(a) Hawser loads, rather than buoy loads, should limit DWP operations.

(b) Allowable hawser loads depend on synthetic rope properties and may be significantly reduced by high loading rates.

(c) There is a need to establish criteria, based on hawser loads and environmental conditions, for determining when to moor, to terminate cargo transfer operations and to leave the mooring.

(5) Types of DWP

(a) SALMs offer greater difficulties for MLMSs than do CALMs, towers or alongside moorings.

(b) LNG DWPs will probably use floating platforms and will probably be quite different from oil DWPs.

ACKNOWLEDGMENT

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Canada Rope
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National Engineering Laboratory (UK)
CONOCO Crude Oil Terminals (Humber) Ltd. (UK)
Hamilton Brothers (UK)
AMOCO (UK) Exploration Company (UK)
Dr. Lloyd Philipson - USC

Western LNG Terminal Associates
National Data Buoy Office (NOAA)
Automatic Power
Mechanics Research, Inc.

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SECTION 1

INTRODUCTION

The U. S. Coast Guard has, subsequent to enactment of the "Deepwater Port Act of 1974" (PL 93-627), been assigned and has accepted responsibility for most aspects of U. S. deepwater ports (DWPs). Two applications for deepwater port licenses were received by the Coast Guard in 1976, and in January 1977 licenses were offered to LOOP, Incorporated and Seadock for construction and operation of ports. LOOP accepted its license in August 1977; this acceptance obligates LOOP to build a DWP in the Gulf of Mexico off the coast of Louisiana.

1.1 Purpose of This Study

The Coast Guard is responsible for insuring the safe operation of any U. S. DWP. The DWP moorings have an important influence on safety, particularly safety of the environment, and on port utilization or efficiency. The moorings must be adequate to withstand the large forces associated with mooring of ships up to 750,000 deadweight (DWT) displacement at an exposed location subject to severe wind, waves and/or current conditions.

The high cost of suspending or delaying DWP operation will produce economic pressures to resist or postpone, as long as possible, any actions which decrease DWP utilization. These actions could range from termination of cargo transfer for one ship to closing of the DWP. Postponing action can increase the danger of accidents. It is, therefore, essential to provide a rational basis, largely independent of human biases, for making decisions affecting DWP utilization.

Most operational DWPs use single point moorings (SPMs). Proposed U. S. DWPs will use SPMs. The ship to buoy hawser is widely recognized as the weak link in the SPM. Failure of the hawser can easily lead to discharge hose damage or failure, with a resulting cargo spill, and can, in some cases, lead to SPM buoy, DWP platform or ship damage. Therefore, it is necessary to provide a sound technical basis for determining when mooring loads reach, or are about to reach, an unsafe level. The purpose of the present study is to evaluate and recommend systems for monitoring (measuring) and predicting DWP mooring loads.

1.2 Objectives and Scope of This Study

The objectives of the study were based on the requirements of the original Coast Guard RFP (CG 64157-A), the HYDRONAUTICS proposal in response to that request (Proposal 33.1273) and on meetings during the course of the contract between Coast Guard and HYDRONAUTICS personnel.

The objectives of this study can be briefly summarized as follows:

(a) Review existing methods for monitoring and predicting mooring loads at appropriate types of deepwater port facilities.

(b) Examine other proposed or possible methods for monitoring and predicting mooring loads.

(c) Define suitable candidate mooring load monitoring systems, including all subsystems and components of each system.

(d) Rank these candidate mooring load monitoring systems, based on performance, reliability, maintainability and cost, and recommend what, if any, system should be installed at a U. S. deepwater port.

(e) Define suitable candidate mooring load prediction systems, including subsystems and components.

(f) Rank candidate mooring load prediction systems, based on potential accuracy, hardware and software requirements, and cost, and recommend what, if any, system should be installed at a U. S. deepwater port.

(g) Examine areas, such as hawser properties, which affect allowable mooring loads and probability or mooring failure.

Each of these areas has been addressed in this study and is described in this report.

1.3 Brief Summary of EXXON Phase I Report

The present study is the second phase of a Coast Guard research program on deepwater port mooring design and loads. It is closely related to, and draws upon, the first phase study carried out by EXXON Research and Engineering Company (Flory, et al., 1977). This report is briefly summarized below.

The EXXON report provides guidelines for the design of a deepwater port single point mooring. It is divided into three general topic areas:

(a) Factors influencing SPM mooring loads and the determination of such loads using model tests, the only method currently acceptable for load determinations according to the report.

(b) Factors which might limit maximum permissible mooring loads including mooring procedures, mooring fittings on the ship, condition, inspection and replacement of the hawser, and human factors.

(c) Guidelines for evaluating mooring system designs, with emphasis on the hawser, and particularly on the hawser rope and fittings.

In addition, background information on several areas related to prediction and measurement of mooring loads, including description of random ocean waves and available facilities for testing ropes and for modeling ships at a SPM, are described in Appendices. A detailed glossary of terms associated with DWPs and SPMs is also given.

1.4 HYDRONAUTICS, Incorporated Trip Reports

A significant part of the results described in this report were obtained during or as a direct result of visits by HYDRONAUTICS personnel to various companies and laboratories in the U. S. and in England. It was not feasible to put all of the resulting trip reports into a form suitable for public distribution. Hence, it was decided not to cite specific trip reports as references as was done in the EXXON Phase I Report (Flory, et al., 1977).

SECTION 2

TYPES AND CHARACTERISTICS OF DEEPWATER PORTS AND MOORINGS

Today a wide variety of DWPs are in use around the world. These include man-made sea islands and various types of SPM's which handle oil and slurries. DWPs for liquified gases are under active consideration. U. S. interest to date has been primarily in oil import terminals, but interest in DWPs for liquified natural gas (LNG) is growing. Existing facilities and the most suitable types of ports and moorings for U. S. applications are considered in this section.

2.1 REVIEW OF EXISTING WORLDWIDE DWPs

Existing worldwide DWPs are primarily of the single point mooring (SPM) type and are used almost exclusively for oil import, export and production. Several SPMs for ore slurry, and several sea island DWPs are in use, however.

A recent article (LeBlanc, 1977) gives a listing and description of more than 200 SPM oil DWPs. Eighty-five percent of these SPMs are CALMs (catenary anchor leg mooring buoys). The other facilities include 12 SALMs (single anchor leg mooring buoys), seven towers, five articulated columns and eight other SPMs which are variations of the CALM and SALM concepts. Recently, there has been much greater interest in and use of SALMs due to their greater suitability for deep water depths and their apparent cost advantage over CALMs.

CALM and SALM concepts are described in detail in the Exxon Phase I report (Flory, et al, 1977) and elsewhere. Brief descriptions of CALMs and SALMs are given below:

CALM - The ship is moored, through a hawser and buoy mounted

swivel or turntable, to a buoy which is moored to the sea floor by multiple anchors and catenary moorings.

SALM - The ship is moored, through a hawser, to a buoy which is moored to a sea floor base or anchor by a single tensioned chain or a rigid link which contains one or more swivels.

Other SPM types include the Single Buoy Storage (SBS) and Single Anchor Leg Storage (SALS) systems which consist of an oil storage ship attached, ususally through a rigid link, to CALM and SALM buoys, respectively. Articulated Loading Platforms (ALP) and Articulated Columns which consist of a bottom fixed, articulated tower or columnar structure, and spar buoys which are large buoys providing large storage capacity. In general, a rigid link is used between the ship and buoy only when the ship is used for storage or production, and will only infrequently be disconnected from the buoy.

2.2 TYPES OF DWPs AND MOORINGS CONSIDERED

The U. S. Deepwater Ports Act of 1974 describes a deepwater port as an offshore, fixed or floating man-made structure to be used as a port or terminal for loading, unloading or handling oil for transportation to any location in the U. S. In this study, facilities which may be appropriate to other products, such as coal or ore slurries, liquified petroleum gas (LPG) or liquified natural gas (LNG), are briefly addressed.

As current U. S. interest in DWPs is primarily for oil importation, this study has placed primary emphasis on CALM, SALM and tower type SPMs, which are ideally suited to this purpose. It has been assumed that the ship and SPM are connected by a hawser, rather than a rigid link, although much of the load monitoring technology discussed is also appropriate to a

rigid link.

Multi-point, alongside moorings, for which there exists a well developed mooring load monitoring and prediction technology, are considered briefly. Such moorings would be used at sea island and possibly at LNG DWPs, which combine cargo transfer and storage capabilities, (Tatge, et al, 1977).

SPMs use two moorings, the buoy mooring and the buoy-ship mooring. Based on various factors discussed below, it was decided to consider in detail only the buoy-ship hawser. Most of these factors were based on discussions with SPM designers and manufacturers of SPM load monitoring equipment.

1. The buoy mooring is designed by well developed methods (ABS, 1975) which incorporate relatively conservative factors of safety.

2. The buoy mooring is generally subject to less abuse and is capable of withstanding much more abuse than the hawser and, unlike the hawser, is not subject to loss of strength through exposure to sunlight and oil or through cuts and abrasion.

3. Breakouts due to mooring failures, appear to have been caused primarily by hawser or ship fitting failure, rather than buoy mooring or buoy fitting failures.

4. A mooring load monitoring system in the buoy-ship mooring is more easily serviced and is less subject to damage than one in the buoy mooring.

Analysis of the LOOP/Seadock model data (Remery and Wichers, 1975) provided further justification for this decision. These data indicate that the buoy mooring consistently operates at a lower percent of its breaking load than does the hawser

and that loads on the buoy moorings in a hurricane are less than maximum loads on the buoy when a ship is moored.

Failure of the buoy or buoy mooring when no ship is moored is generally a less serious safety problem. At a SALM facility the discharge hoses can be completely flushed with sea water. Oil can be spilled only during discharge operations. At a CALM facility flushing of the hoses is not possible and a failure, even of an unoccupied buoy, can result in a spill.

SECTION 3

REVIEW OF DWP MOORING LOAD MEASUREMENTS

3.1 INTRODUCTION

The mooring system for any type of port facility is composed of a number of elements which, combined with the vessel, constitute a complex mechanical system. This system, excited by forces due to wind, waves and currents, can be considered, in terms of classical mechanics, as a dynamic network. Two methods for describing the dynamic behavior of the SPM-ship system are given in the references (Filson, 1974; Flory, et al. 1977).

The purpose of making load measurements in mooring systems is to determine static and dynamic forces acting on the various elements and to ensure that these forces do not become great enough to cause damage or failure of any element. Failures which lead to dangerous or environmentally damaging situations, particularly oil spills and perhaps LNG spills, are of greatest concern.

Discussions of operating experience with mooring component designers and manufacturers, rope manufacturers, and operators of deepwater ports have generally singled out the hawser assembly as the component of primary concern. In particular the rope, rather than chafing chains, shackles or other hardware, is viewed as the component most likely to break. Ideally load measurements should be made in the rope. Although this has been considered, it has not been done to date because of the hostile environment for and the high probability of damage to an in-rope transducer. Systems presently in use make force measurements at or near one end of the hawser assembly. Equipment in use or planned for the various types of deepwater port facilities are listed in Tables

3-1, 3-2 and 3-3.

3.2 EQUIPMENT IN USE OR PLANNED FOR CALMS

Table 3-1 lists most of the load monitoring equipment which has been used on SPMs around the world. This table, together with Tables 3-2 and 3-3, provides a good survey of existing mooring load monitoring techniques. It is obvious from Table 3-1 that most of the load measurement experience has been at facilities which use CALMs. This is not surprising since 85 percent of all SPM installations are of the CALM type. It is also obvious that strain gage load cells are the preferred sensors and radio is the preferred method of signal transmission. The type of sensor used is not strongly dependent upon the type of mooring; however, the type of signal transmission is strongly dependent upon the type of mooring and the general layout of the port. Radio transmission works well with CALM buoys since the buoy deck is rarely, if ever, submerged. It is possible to lose the radio signal for a short period if a very large wave washes over the antenna, but the frequency of occurrence is too small to be a problem.

The operating experience with load monitoring equipment on CALM buoys has generally been good. Table 3-1 gives a summary of the equipment with comments. Some pertinent observations on equipment type and problems are:

1. Two types of transducers have been used successfully in sensors. Shell used a linear variable differential transformer (LVDT) transducer at Anglesea. All other CALM installations have used strain gage load cells.

2. Radio has generally worked well for signal transmission. IMODCO has experienced some difficulty with drift, but the source and type of drift was not specified.

3. The ship can, in some positions, block VHF or UHF radio transmission; however, at the Algerciras facility this problem was cured by changing to HF radio (27 MHz).

In addition to the facilities listed in Table 3-1 many of the dedicated ships with systems described in Table 3-3 operate at facilities with CALM buoys.

3.3 EQUIPMENT IN USE OR PLANNED FOR SALMs

Although the SALM is a relatively recent design of SPM (first installation in Libya during 1969), it use is growing rapidly since it appears to be better suited for deep water use and more economical than a CALM. The SALM concept is especially important to this study because it was the preference of both LOOP and SEADOCK, in the environmental analyses accompanying their license application. To date, very few load monitoring systems have been installed on SALMs.

The British National Oil Company Thistle Field facility (Table 3-1, Item 5) has a load monitoring system which was installed in 1977. The buoy is anchored by an articulated riser with two universal joints, rather than by a chain. This buoy was designed to moor ships up to 80,000 DWT, but will be used for ships up to 120,000 DWT. Consequently, it was decided to measure the angles of the two riser legs, in addition to the hawser loads, to ensure the angles of the riser/buoy were not excessive. The load sensor is a strain gaged shear mooring pin on the buoy, and the angle transducers are pendulum inclinometers. The load sensor and the angle transducer for the upper half of the riser are connected by armoured cable to a waterproof electronics package mounted on the buoy deck. The output of this electronics package is fed to an acoustic transmitter.

Once every second data is transmitted to the ship. Upon receipt of this data the shipboard electronics transmits an interrogate pulse to one of the lower riser leg transponders. The appropriate transponder is turned on and a data point is transmitted. After transmitting data, this transponder returns to the listening mode. Two other systems (which are about to be installed on CALMs) are listed in Table 3-2.

Although no significant operating experience has been obtained with any of these systems, their designs emphasize the differences between CALM and SALM installations. The frequent submergence of SALM buoys makes the use of radio telemetry impractical. To date the solution has been to telemeter data using an underwater acoustic link.

3.4 EQUIPMENT IN USE ON DEDICATED SHIPS

When dedicated ships are used at a SPM facility the hawser load monitoring problem can be simplified. This is true regardless of the type of SPM used. Table 3-3 lists some systems which have been used on dedicated ships.

Samson Ocean Systems has installed their traction winches on a number of ships. Some of these incorporate a simple load monitoring system which uses pressure transducers on reaction arms in the winch to sense torque. This in turn is calibrated to display the load in tons of force. In at least two cases measured load is also displayed on a strip chart recorder located on the ship's bridge.

Hamilton Brothers have Samson traction winch systems installed on two ships which are used in the Argyle Field, U. K. North Sea (Barr, 1977e). The original system was equipped with Martin Decker sensors on the reaction arms for each drum.

The meter read-out was housed in a small deckhouse near the bow. Since some damping is most likely present, the system may not accurately give peak or snatch loads. The system was modified by Strainstall, Ltd. New pressure transducers were added and a paper chart recorder display was placed on the ship bridge. Figure 3-1 is a typical chart recording from that system. The two hydraulic systems give comparable results up to 25 percent of allowable load, but significantly different results at 75 percent. The reason for this difference is not known, but may be due to the inability of the original system, with meters, to indicate true peak loads.

Amoco, has equipped two ships with Samson mooring systems for use at the Montrose Field, U. K. North Sea. At the present time a mooring load meter is located in a special wheelhouse near the bow of the ship. A seaman relays load information to the bridge by two-way radio, however, a new system is being studied which would have a chart recorder on the bridge. Variables other than mooring load which might be recorded are wind speed and direction, and perhaps wave height or tanker motions.

Shell has instrumented four ships for use in the AUK field (U. K.). The sensors are strain gaged shear pins, provided by Strainstall, Ltd., that are installed in bow chain stoppers. These pins are of the same type used at SPM and alongside installations.

Although equipment used on a dedicated ship has no direct application at a U. S. DWP such as proposed by LOOP or SEADOCK, the operating experience gained at these facilities is useful in defining MLMS requirements.

3.5 EQUIPMENT IN USE ON ALONGSIDE MOORINGS

A VLCC moored alongside a pier, a sea island or a large barge utilizes a large number of lines. At such moorings it is difficult to ensure that all mooring lines share the load equally. Full-scale mooring load measurements, carried out by the National Engineering Laboratory (NEL) and described in Appendix A, indicated that, for a typical pier, 95% of the total mooring load was being taken by not more than three of a total of twenty mooring lines.

Mooring points on large tanker berths generally are quick release hooks or similar devices. The NEL developed a strain gaged shear pin load cell that can replace the pin in those devices. Strainstall, Ltd. and British Hovercraft Corp. have used the shear pin load cells in systems which monitor the load in all lines from a ship to the berth. Strainstall, Ltd. has installed such systems at an EXXON facility at Southhampton, England and at a Canadian Navy facility in Newfoundland. British Hovercraft Corp (BHC) has also installed similar systems. These systems apparently work very well. At Milfordhaven ships are not permitted to moor or remain moored if the MLMS is not working.

Most of the mooring load monitoring systems in use at SPMs utilize a meter or paper chart recorder with a high level alarm; however, more elaborate displays have been developed for use at berths with multiple hook systems. Strainstall has used a histogram display with a diagram showing a ship and all the lines in use (Appendix A). BHC has used histogram displays at Kharg and Milfordhaven. Ocean Technical Services (OTS) has proposed providing a multiple color CRT display in which the load in each line is displayed as a colored bar. When the bar (load)

exceeds a preset maximum the color changes from green to red. If the load drops below a preset minimum the bar color changes to blue (or yellow). At a deepwater port with multiple SPMs and MLMSs this type of display could be useful for rapid review of loads on all moored ships.

The Samson Traction Winch system could be used at alongside moorings. This provides the advantage of a ready means for monitoring line load and for correcting load as necessary.

3.6 PRESENT ABILITY TO MEASURE AND RECORD MOORING LOADS

Several types of mooring load monitoring systems have been designed and built. A number of systems have been installed at SPMs and alongside berths for mooring ships to 500,000 DWT. These have generally operated successfully. It is obvious from preceding sections that the number of systems installed at facilities with single point moorings is increasing. Comments by equipment manufacturers and operating personnel at facilities with functioning mooring load monitoring systems indicate the value of such systems:

1. One operator described the load monitor as the best investment they ever made. They didn't know when to take decisive action, from safety and operation standpoints, before the installation.

2. Another operator reported that the load monitoring system had increased utilization by about 20 percent.

In addition to such comments, many chart recordings exist which clearly show that mooring load measurements cannot only be made but can serve as useful tools for DWP operation. At several facilities chart records are used as a basis for instituting rudder steering which can significantly reduce the loads

in the hawsers (Linehan et al., 1975).

Finally there are at least three manufacturers who offer off-the-shelf monitoring equipment. Strainstall, Ltd. and OTS/BHC offer systems for use at SPMs and at alongside berths. Samson Ocean Systems provides an integral load monitoring system with their traction winches which can be used on dedicated ships at SPMs or at alongside berths. Automatic Power has provided simple on-buoy systems which do not telemeter the load data, but flash lights at different rates when the load exceeds preset levels. Mechanics Research, Incorporated can provide a simple system, although to date has not done so. Appendix A provides a more detailed "Description of Actual Measurement Systems In Use At Present."

TABLE 3-1

MOORING LOAD MONITORING SYSTEMS INSTALLED ON SPMs

Owner or Operator	Facility or Country	Type of Mooring	Type of Sensor	Type of Signal Transmission	Supplier of Equipment	Comments
1. Conoco	Tetney, U.K.	CALM	Strain Gaged Tensile Cell	UHF Radio	OTS/BHC	Installed 1974 (Barr, 1977c)
2. Petrobras	Brazil	CALM	Strain Gaged Cell on Buoy Load Bearing Member	Radio-Warning Lights on Buoy	IMODCO/ Automatic Power, Inc.	Installed 1974: Sensor worked well but radio transmission was a problem
3. Shell	Anglesea, U.K.	CALM	LVDT Instrumented Triangular Hawser Attachment Plate (500 Ton Capacity)	UHF Radio	IHC-Sensor OTS/BHC-Radio and Display	Installed March 1977: System has worked well
4. Occidental Oil	Scappa Flow, U.K.	Two Instrumented Pile Supported Towers	Strain Gaged Tensile Cell (500 Ton Capacity)	Two Way UHF Radio	OTS/BHC	Remote ON-OFF Control and Battery Check: System has worked well.
5. BNOC	Thistle Field, U.K.	SALM with articulated riser	Strain Gaged Shear Pin: Also measure upper and lower riser angles	Acoustic link to dedicated ships	OTS/BHC	Sea trials completed December 1977: four dedicated ships
6. Cepsa	Algerciras	CALM	Strain Gaged Shear Pin	UHF Radio changed to HF Radio	Strainstall Ltd.	
7. Hamilton Brothers	Argyle Field, U.K.	CALM	Not Known	None-uses 3 warning lights	IHC	This system has problems but because of weather in North Sea they rarely can get on buoy to check it.
8. CPC	Kaohsiung	CALM	Strain Gaged Cell-on buoy load bearing member	Warning lights on buoy	IMODCO/ Automatic Power, Inc.	
9. Unknown	Nigeria	CALM	Strain Gaged Cell-on buoy load bearing member	Radio warning lights and recorder on buoy	IMODCO/ Automatic Power, Inc.	Problems with radio trans-mission due to nearby transmitters.

TABLE 3-2

MOORING LOAD MONITORING SYSTEMS ON ORDER FOR SPMs

	Owner or Operator	Facility or Country	Type of Mooring	Type of Sensor	Type of Signal Transmission	Supplier of Equipment	Comments
1.	Occidental Oil	Libya	CALM	Strain Gaged Shear Pin	Radio	OTS/BHC	Installation in Progress for three CALM buoys. Installation due June 1978.
2.	New Zealand Steel	New Zealand	CALM	Strain Gaged Shear Pin	Radio	OTS/BHC	Commissioned January 1978.
3.	Waipipi Iron Sands, Ltd.	New Zealand	CALM	Strain Gaged Shear Pin	Radio	OTS/BHC	Installation expected July 1978.
4.	Aramco	Saudi Arabia	CALM	Strain Gaged Shear Pin	Radio	OTS/BHC	Installation due October 1978.
5.	Exxon	U.S.A.	SALM	Strain Gages	Cable With Inductance Coupling	Interstate Electronics	Under construction.

TABLE 3-3

MOORING LOAD MONITORING SYSTEMS ON DEDICATED SHIPS

	EQUIPMENT MANUFACTURER	SYSTEM TYPE	NUMBER OF SHIPS	COMMENTS
1.	Samson Ocean Systems	Pressure Gages or Transducers on Reaction Arms of Traction Winch	9	Ships moor to SPM using Traction Winch. Pressure is converted to tons load and displayed on Meters or Chart Recorders.
2.	Strainstall, Ltd.	Shear Pins in Bow Chain Stopper	3	Used by Shell in Auk Field, U.K.-SPMs
3.	Strainstall, Ltd.	Shear Pins in Bow Chain Stopper	2	Used by Hamilton Brothers at Argyll Field
4.	Strainstall, Ltd.	Shear Pins in Bow Chain Stopper	4	Used by BNOC at Thistle Field
5.	Strainstall, Ltd.	Shear Pins in Bow Chain Stopper	1	On Tanker Esso Aberdeen (Field unknown)
6.	OTS/BHC	Receiving Electronics Only - Acoustic Link	4	Used by British National Oil Co. at Thistle Field, U.K.-SALMs

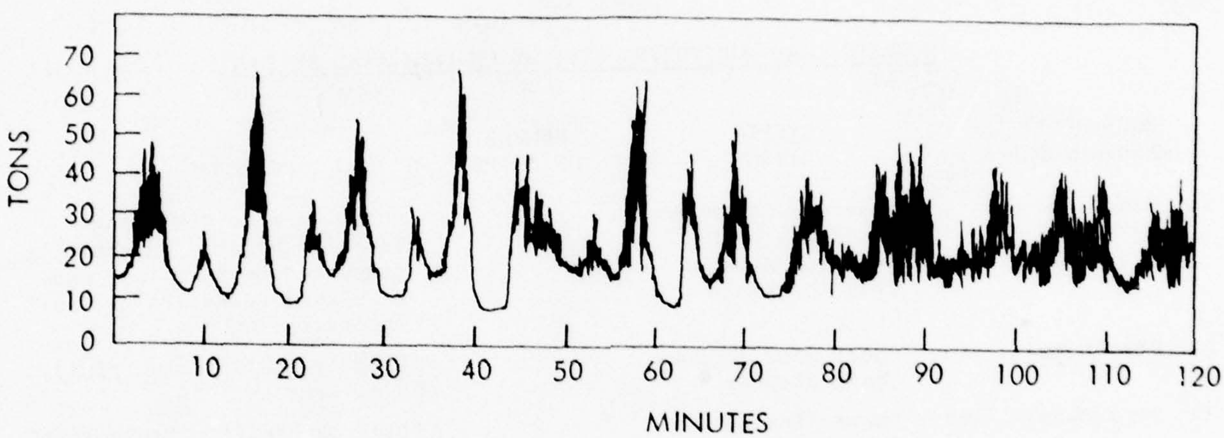


FIGURE 3-1 - TYPICAL CHART RECORDING FROM MLMS (SOURCE - SAMSON OCEAN SYSTEMS - HAMILTON BROTHERS, ARGYLE FIELD)

SECTION 4

DESCRIPTION OF MOORING LOAD MONITORING SYSTEM

4.1 INTRODUCTION

The term Mooring Load Monitoring System (MLMS) is now generally accepted to mean any systems which will measure the forces, static and dynamic, in SPM mooring hawsers and mooring lines at alongside berths. An integral part of the system is a display, such as a meter or chart recorder typically calibrated in tons of force, and equipment to sound alarms when the forces exceed a preset level. In this study a MLMS is further defined as consisting of the following subsystems:

1. Load Measurement
2. Data Handling
3. Load Warning
4. Data Display

In addition, if a Mooring Load Prediction System (MLPS), such as described in Section 6 is used, it will interface with the MLMS. Each of the above subsystems and its components are discussed in detail in this section.

4.2 GENERAL REQUIREMENTS FOR A MLMS

It would be relatively easy to assemble a MLMS from available components if it were not to be used in an ocean or DWP environment. It is a common misconception that any good electronic equipment can be mounted in a "Waterproof Can" and used in the ocean.

The NOAA Data Buoy Office (NDBO) has acquired a great deal of experience in deploying electronic measurement systems, comparable in complexity to the MLMS, on unattended ocean buoys. In 1973 the NDBO published a document (NDBO, 1973) detailing

their experience. In the section "Performance Based on Experience" (Large Buoys), the report states: "The primary reason for performance below the predicted rate was due to onboard equipment failures.......... What the performance of the buoys has borne out is that equipment specifically designed for buoy application seems to work. Equipments that were essentially selected from off-the-shelf inventory has not measured up to the level of performance delivered by the custom design equipments." A survey of existing mooring load monitoring systems produced a somewhat similar result.

As explained in Section 3, mooring load measurements have concentrated on forces in the hawser assembly. Consequently the following general specifications for a mooring load monitoring system can now be listed:

1. It must accurately measure tensile forces in the hawser assembly with ships up to 750,000 DWT on the moor.
2. It must operate unattended for significant periods of time, and during periods of severe storms.
3. The required maintenance must be minimal and repairs, or component replacement, must be effected in situ.
4. All components of the load measurement subsystem must withstand repeated submerging without damage or impaired performance.

With the general system requirements defined, the individual components can be defined and analyzed.

4.3 DEFINITION OF SUBSYSTEMS AND INTERFACES

A block diagram of general Mooring Load Monitoring and Prediction Systems is shown in Figure 4-1. The systems are

divided into subsystems (blocks), and the interfaces are shown. Components which could be included in the various subsystems are listed in each block. The components comprising a subsystem may vary with the overall system requirements. However, it should be noted that all of the components listed in the measurement subsystem block are required in any useful system.

A block diagram of what is considered to be a minimum useful system for a DWP is shown in Figure 4-2. This is essentially the system marketed by Ocean Technical Services and Strainstall, Ltd., and installed, or being installed, at a number of SPM facilities. Simplier systems have been used, but are considered to be inadequate for U. S. DWP use.

A block diagram of a system configuration recommended for initial use at U. S. DWPs is given in Figure 4-3. It includes all of the components in the minimum useful system of Figure 4-2, and two additional components. The first is a time history display, such as a small oscilloscope, on the ship's bridge. The second is an automated short term prediction system, such as described in Section 6.3.2, at the control center and on the ship's bridge. If the ship's bridge is not manned, equipment may be located in the pump control room.

After a DWP has been in operation for 1 or 2 years and has accumulated sufficient data, the MLMS of Figure 4-3 can be expanded, as shown in Figure 4-4. This system contains automated short-term and medium-term prediction schemes.

4.3.1 Load Measurement Subsystem

The load measurement subsystem is the heart of a MLMS. It consists of the following components:

1. Sensor(s)
2. Signal Conditioner

3. Transmission Link
4. Power Supply

In Figure 4-1 the receiver is shown separate from the measurement subsystem block. This is because it is located in the control room and/or on the ship rather than on the SPM with the other components. In practice it must be selected with the transmitter as part of the signal transmission link. The load measurement subsystem interfaces all of the other subsystems.

4.3.2 Data Handling Subsystem

A data handling subsystem is not essential in a minimum configuration such as shown in Figure 4-2. However, it becomes essential as the system is made more complex; for example, when measured loads or environmental data (wind velocity, wave height, etc.) are used in an automated prediction scheme or to build a data base for future use and analysis. Some items which might be included in a data base are:

1. Hawser age
2. Hawser loading history (cycles vs force)
3. Ship characteristics
4. Quality of fittings of ships which have visited port.

In addition, short term data storage could be used for inputs to the load warning subsystem and the prediction system. The use of stored data in prediction systems is described in Section 6.

Input interfaces are from the measurement and load warning subsystems and prediction system. Output interfaces are to the load warning subsystem and load prediction system.

4.3.3 Load Warning Subsystem

The load warning subsystem will incorporate one or both of two basic methods. The first method, in common use on

present systems, consists of a signal comparator which, based solely on the comparison of load to a set value, triggers an alarm.

The second method consists of a computer program which examines peak loads plus other input factors and determines the safe load limit at the present time. The comparison of measured and allowable load would be made in the computer, but the alarm hardware might be the same as the type used in the first method

The input interfaces are from the measurement subsystem, data handling subsystem, operating personnel and the prediction system. The output is directly to port operating personnel and the ship's master.

4.3.4 Data Display Subsystem

The data display subsystem can take many forms. Present MLMSs generally use meters and/or strip chart recorders. In some systems the recorders are turned on automatically when the load exceeds some preset minimum value. In a system which utilizes a computer for data handling, load warning or prediction, some type of digital display could be used. Video displays and CRT terminals with graphics would be very useful when an operator must monitor multiple loads. These may be loads of several lines from one ship, as described in Section 3.4, or loads from several ships. The input interfaces for this subsystem are from the load measurement and the load warning subsystems. The output is directly to port operating personnel and the ship's master.

4.4 LOAD MEASUREMENT SUBSYSTEM COMPONENTS

It was stated in Section 4.4.1 that the load measurement subsystem is the heart of the MLMS. The components of this subsystem are the sensor, signal conditioner, transmitter/receiver and power supply. Each component must be designed specifically

for use in the deepwater port environment.

4.4.1 Sensors

The terms sensor and transducer are often used interchangeably. In this report transducer is understood to be a device capable of being actuated by signals from one or more transmission systems or media and of supplying related signals to one or more transmission systems or media. More specifically, the definition of an electromechanical transducer, a transducer for receiving signals from a mechanical system and delivering signals to an electric system (or vice versa), is used. A sensor is defined in this report to be a device which provides an electrical signal that can be related to mooring force. It contains the transducers, mechanical couplings, hardware (packaging, mounting, etc.) and electrical connectors necessary to perform its function. For example, a load cell, which is a sensor, generally consists of a mechanical flexure, transducer (often strain gages), an electrical circuit (bridge resistors) and an electrical connector. It is supplied with a calibration curve relating output voltage to input force. In summary, a sensor is related to the engineering problem of obtaining a signal, whereas a transducer is related to the physics of converting energy from one media to another.

Transducers are reviewed in detail in Appendix B1. Some basic types of transducers (see Truxall, 1958) considered are:

1. Variable Resistance
2. Magnetic Field
3. Electric Field
4. Bulk Effect such as Magnetostrictive and Piezoelectric
5. Miscellaneous such as Control of Oscillators, Mechanical Resonances, and Media Changes which produce Phase Changes, etc.

Each type is reviewed for its applicability in the various types of sensors.

Some general sensor specifications are given in Table 4-3. The different kinds of sensors are rated and compared in Table 5-2. Four applications of sensors are considered:

1. Sensors at either end of the hawser
2. Sensors in or on the buoy structure
3. Sensors in or on the hawser
4. Sensors for indirect measurement of mooring loads.

Most existing MLMSs use sensors at one end of the hawser. Since the Samson traction winch, which uses a load monitoring system based on hydraulic pressure, is unlikely to be used at U. S. DWPs, it is not considered further. All installations listed in Table 3-1 use either a strain-gaged load cell (shear pins or tension links), a LVDT load cell (Shell Anglesea facility), or a strain-gaged cell mounted on a buoy load bearing member. *Shear pins are likely to be used in most new installations.* These sensors weigh about 70 lbs. compared to 1,300 lbs. for the original OTS/BHC tension links. Load cells based on flexures with other types of transducers (such as variable capacitors, or piezoelectric cyrstals) can be used; however, it is doubtful that any of these would be better than strain gages and few would work as well. Transducers which have moving parts (such as potentiometer sliders and variable reluctance moving cores) are susceptible to damage in the SPM environment. Any sensor permanently installed in the ship end of the line would be very susceptible to damage when no ship was moored and during the mooring operation. Moreover, if the line is not free (for instance, it may rub on the fairlead) the sensor will not accurately measure the total forces, and higher frequency components may be attenuated.

Sensors may be attached to or mounted on load-bearing members of the SPM buoy. This technique has been used successfully by IMODCO. These sensors could use any type of transducer which functions well in a SPM environment. Strain gages have been used successfully on IMODCO buoys. The major disadvantage of this technique is, again, that the forces measured may be less than the forces in the hawser. This is particularly likely for higher frequency components.

The possibility of mounting sensors or transducers (such as strain gages, pressure cells, etc.) in or on the hawsers has been examined and discussed with rope manufacturers, port operators and others. The most common cause of hawser failure is cuts and abrasions of the rope. Also, the rope is continually stretching and storing or releasing large amounts of energy. This is a very hostile environment for transducers, cables and electronic components in general. A great deal of research and development would be required to develop such techniques.

Three measurement techniques using sensors which might be used to indirectly infer the mooring loads or to directly predict a rope failure, have been considered. The first technique is to implant temperature sensors in the rope. Heat is generated by friction between strands of a rope under heavy loading or when the rope passes over fairleads, bits, etc. The heat is related to hawser load, and can, near ultimate load, be sufficient to melt or fuse some fibers. The temperature rise due to interstrand or fiber friction might be used as a measure of the load. High temperatures, whatever the reason, would indicate probable damage to the rope. Unfortunately there are many difficult problems in making and using such temperature measurements. The difficulty of mounting transducers of any kind in or on the rope has been discussed. Furthermore, it is not clear that temperature can reliably be related to load. It is very improbable

that the temperature would be uniform throughout the rope. Also the heat transfer characteristics change with the environment (wet or dry rope, wind, etc.). Most importantly, rope temperature eventually returns to ambient under a static load and therefore could not be used to indicate static loads. Finally, a temperature rise sufficient to cause weakening (or fusing) of strands or fibers can occur at any location so that many transducers are required for adequate results.

The second technique considered is the use of acoustics. Sound pressures generated by the rope as it stretches, or changes in acoustic properties, such as impedance, could be measured. In either case the problems are essentially the same as those encountered in measuring temperature:

1. Difficulty in relating measured quantities to load.
2. The high probability of damage to transducers.
3. Sound pulses are not generated in the static case.
4. Environmental factors, such as line wetness, affect the acoustic properties.

If transducer and environmental problems could be solved, one might use acoustics (or temperature) to sense impulse (snatch or shock) loads. This could be very important since such loads can break a rope at relatively low load levels as described in Section 8.3. Extensive research would be required to make a workable system.

Finally, rope elongation under load (stabilized ropes) could be measured and used to determine when a rope is in danger of breaking, as described in Section 8.1. Shell Oil Company has instituted a program at Anglesea of measuring the elongation of hawsers under known applied loads. The hawser is removed from the SPM and its length measured for a small load (not given) and fifty-ton loads. Unfortunately there is presently

no known method of making in situ (on the SPM) measurements of hawser elongation. This is one area where some research could pay large dividends.

4.4.2 Signal Conditioning

The design or selection of a signal conditioner presents the least problems of any component in the load measurement subsystem. The output of most transducers requires some aplification and scaling to obtain a signal calibrated in engineering units. The form of the electrical output signal may be analog, digital or a modulated frequency. The form selected will depend on the type of communication link, data display and warning subsystems used. Analog and digital signals degrade very badly when transmitted over very large distances; therefore, some type of modulated carrier transmission link will generally be required. Either amplitude (AM) or frequency (FM) modulation can be used; however, FM is far superior to AM in noise rejection and is used in most telemetering systems. If a signal is sampled, the sampling rate must be high enough to preserve the highest frequency of interest. Most existing systems have very low sampling rates because high rates of loading have not been considered.

The availability of high quality solid state components has made possible the design of a wide variety of small, rugged, light weight, reliable signal conditioners. In fact, the signal conditioner is now built into many sensors. Many of these convert the tranduced signal directly into a digital or a variable frequency (FM) output. In general, the incorporation of the signal conditioner into the sensor is desirable.

4.4.3 Data Transmission

The design of the data transmission link is comprised of two parts -- the selection of the form of the transmitted signal and the selection of the proper hardware. The form of the

signal is discussed briefly in Section 4.4.2. If the complete analog signal is to be transmitted, FM is the best choice of modulation regardless of hardware. A sampled data system, in which only the value of the signal at discrete intervals is transmitted, can provide significant power savings. This is particularly important if batteries are to supply the power on the SPM buoy. The samples (pulses) can be transmitted by a variety of modulation schemes (Westman, 1959). Several pulse modulation techniques are shown in Figure 4.7. One scheme which has been used to transmit data from a SALM by an acoustic link uses pulses of different frequencies. The time between pulses of two different frequencies represents the amplitude of the data sample. A second channel can be added by transmitting a pulse of a third frequency.

The data can be digitized before transmission. A common method of transmitting digital data is frequency shift keying (FSK). A pulse of one frequency represents a binary one and a pulse of a second frequency represents a binary zero. This type of data can be transmitted reliably, but only with increased amounts of equipment and power consumption (compared to sampled data) at the sensor location. Since there is no obvious advantage to digitizing mooring load data before transmission, this technique is not recommended.

An initial study of transmission equipment has narrowed the choice to radio, acoustics and underwater cables. Radio has been used successfully on CALM buoys. The frequencies used have been in the VHF and UHF bands; however, HF was used successfully at one installation to eliminate a problem of loss of signal whenever the ship lay between the SPM and the receiving station. Unfortunately radio is not a viable alternative for use on SALMs which frequently submerge under heavy loading.

Although none of the MLMSs listed in Tables 3-1 and 3-2 used underwater cable for signal transmission, cables could easily be used at many CALM installations. CALMs, unlike SALMs, are not designed to submerge. Moreover, the mooring hawser generally connects to a rotating mooring arm on the buoy, and the cargo hoses connect to a swivel on the buoy. The buoy does not rotate; therefore, a cable can be suspended in a catenary fasion from the bottom of the buoy to the ocean floor. The feasibility of using cables with SALMs depends on the type of SALM, depth of water, and probably on the development of special equipment such as slip ring assemblies in underwater swivels.

A cable will be used at the Exxon Hondo facility at Santa Barbara, California, to carry large amounts of power from a SPM to a platform (Pieroni and Fellows, 1977). This SALM, which is in 490 feet of water, has risers with two universal joints. One is approximately 160 feet below the water surface and one is at the base. A swivel, which allows a moored ship to rotate around the SPM, is located inside the buoy. The underwater electrical cable terminates at the swivel in a relatively good environment. Inductive coupling is used to pass MLMS signals across the swivel. Tests were conducted (Pieroni and Fellows, 1977) which indicated that a cable, attached to the SALM riser, which has a compressive loop across each universal joint, can operate for a satisfactory period of time (up to 30 years). Nevertheless, it was decided to suspend the cable, in a catenary fashion, from the bottom of the buoy to the ocean floor. Figure 4-5 depicts both of the above techniques for using underwater cable.

With chain anchored SALMs in 100 feet of water (such as planned for the LOOP, Inc. DWP) the use of cables would be more difficult. With such a SALM, Figure 4-6, the cargo hoses are generally attached to a swivel at the bottom of the chain. A

cable suspended from the bottom of the buoy would interfere with the cargo hoses, and could be struck and damaged as a large ship moves close to the buoy. Thus, with this type of SALM, it becomes necessary to clamp the cable to the chain and provide a flexible loop across the universal joints. This is possible because the chain is so heavily pre-tensioned that it cannot twist. In addition, a means, such as electrical slip rings or inductive couplings, must be provided to pass the signals across the swivel.

Several companies have built electrical slip rings into swivels which are located in watertight compartments of the buoy. During this study no one was found who has successfully built slip rings into underwater swivels.

SSP Construction examined, for Exxon Research and Engineering, the possibility of building slip rings into an underwater swivel. They concluded that, while it should be possible, considerable research and design will be required. Their tests of an eight and one half tone prototype unit were unsuccessful. The primary problem was leakage of water at the electrical connectors and penetrators. Passing electrical cable through or into load bearing members is a major problem.

Since electrical cables and connectors have been the source of many problems in ocean systems, much research has been done on their use. Even short cables (with connectors) on ocean buoys (NDBO, 1973) have been the source of problems. Several manuals and handbooks (Paradis 1976, Forbes, et al., 1970 and Regan 1971) provide a great deal of information on waterproofing cables, connectors and bulkhead penetrators.

Acoustics appears to be the most developed choice for SALM use as the third method of transmitting signals from SPMs. The performance of an acoustic transmission link will depend on the distance the signals must be transmitted and the ambient noise level at the SPM. A paper presented at MTS-IEEE Oceans 77

(Becker/Pence 1977) discusses the acoustic environment in the vicinity of two NOAA discus buoys. Measurements were made at 10-meter intervals from the surface to a depth of 70 meters. The transducer array was suspended in a horizontal position at 13 meters. All measurements were made under sea state 2 and wind force 3 conditions. The conclusions of this study are:

1. The noise levels in the vicinity of moored data buoys are significantly higher than open-ocean noise.

2. Many impulse noise bursts were measured near the buoys. These transients, numerous and high-level, ranged from 5 to 20 dB above the general noise background.

The impulsive noise bursts are potentially the greatest problem. Similar measurements should be made in the vicinity of SPM buoys to see if such impulses occur because of mechanical resonances in the buoys. Another Oceans 77 paper (Cybulski, 1977) discusses supertanker radiated noise spectra. Ships entering or leaving the port are another potential source of noise.

It is generally felt that with proper equipment acoustics could be used to transmit data up to one mile. Noise, power and accuracy requirements may limit the practical range to something considerably less than a mile; however, the signal could be relayed to a control platform as proposed by LOOP and SEADOCK. An underwater acoustic receiver could feed the signal to another acoustic transmitter, a radio mounted on a small-nonsubmerging buoy or an underwater cable. The best means of relaying the data would depend on a number of factors including cost and the general layout of the port.

The area directly beneath the buoy is a poor location for any electronic equipment because of the danger of heavy falling objects (such as shackles and other hardware). The acoustic

receiver must be located beyond this area, or protected from damage. One possible acoustic transmission link configuration would be a transmitter suspended directly below the buoy and a receiver located somewhere between the buoy and the control platform. The signal would then be relayed, by one of the methods discussed above, to the ship, to a control platform or to shore. Another possible configuration would be to use acoustics to bypass the swivel. An acoustic transmitter could be suspended from the bottom of the buoy or attached to the chain above the swivel. Receivers located near the base (protected from falling objects) would feed the signal to an underwater cable which goes to the platform.

In the above discussion, it is assumed that data will probably be transmitted from a SPM to a nearby DWP control platform. This is the most likely link at U. S. deepwater ports; however, a number of other links are possible. Direct transmission from the SPM to the ship or to shore would be used only as a redundant link or where there is only one SPM with no control platform close by. Transmission to shore could be direct by radio or relayed by satellite. Transmission to the ship would have to be by radio or acoustic links. Transmission of data from the ship to a control platform or ashore would probably only occur as a redundant link or if the sensor were located on the ship. Transmission links involving the ship require that equipment be carried aboard. This is not a good practice for a number of reasons: the weight of equipment carried aboard is limited; there is a risk of dropping it in the water; the more that equipment is handled, the more likely it is to be damaged.

Some transmission links and methods are compared in Table 5-3. Some general specifications are given in Table 4-3.

4.4.4 Power Supply

Although there will be ample power available at deepwater ports for most of the MLMS equipment, components located on a SPM, particularly on a SALM, probably cannot obtain power from the main supply. In this case it will be necessary to store and/or generate energy on the buoy. Batteries are widely used for all types of oceanographic instruments and equipment, including most of the mooring load monitoring equipment in present use.

There are so many batteries available with such widely varying characteristics that the choice of a battery can only be made for a specific application. Some of the factors which must be considered in choosing a battery are:

1. Nominal and Minimum voltage.
2. Current drain and schedule of operation (continuous or intermittent duty).
3. Capacity (ampere-hours) at expected temperature.
4. Temperature - Operating and Storage.
5. Environment - Shock and Vibration, Acceleration Orientation (Vertical, etc.), Humidity.
6. Design into a system - type of terminals, packaging (waterproofing), etc.
7. Maintenance.
8. Economic Comparison.
9. Self Discharge Characteristics.

Tables 4-1 and 4-2 list some typical battery types and representative characteristics. Three references are listed which provide additional information (Mantell, 1970; Jasinski, 1966 and Fink and Carroll,1956). These charactersitics vary with manufacturer and can even vary with the type of use. For example, the capacity (ampere-hours) and terminal (plateau) voltage may be very dependent on the rate of discharge and/or the duty (intermittent or continuous). Operating temperature, as seen in

Table 4-1, can vary widely for different types of batteries. Another important consideration for unattended use is the self-discharge characteristics. Some types of batteries discharge rather rapidly when not in use. Finally, the cost, or cost per unit of energy (dollars/watt hour) is a very important consideration.

Air (or air-depolarized) batteries have been used on SPMs with MIMSs, and on NDBO buoys. Carbon-zinc and alkaline-manganese batteries have also been used on NDBO buoys (NDBO, 1973). Each type has its strengths and weaknesses. Air batteries have good energy density and cost, but require ventilation. Carbon-zinc batteries are low cost with fair energy density, but their low temperature characteristics restrict their use in cold climates. Alkaline-manganese-dioxide batteries have good energy density and temperature characteristics, but their cost is high.

Secondary (rechargeable) batteries can also be used where it is possible to recharge them. One major problem in recharging is the ventilation of gases. One company manufactures a nickel-cadmium battery for underwater use. If it is charged to only 60 percent of capacity, ventilation is not required. Secondary batteries, recharged from primary batteries, have been used to supply peak loads such as those required for transmission of signals; however, this is not considered to be a particularly good method because additional charging and regulating circuits, which tend to reduce system reliability, are required. Any time that secondary batteries are used in an enclosed compartment there is a possibility that gases can accumulate. Consequently there is a danger that workmen, using tools to enter the compartment, may cause a spark which ignites the gas.

Several schemes such as solar cells and wave generators have been considered for recharging batteries. A relatively large number of solar panels have been used on platforms and

buoys. These panels recharge batteries which power navigation aids such as lights and horns. A recent article in "The Oil and Gas Journal" (Noran, 1978) described several applications of solar panels including one on buoys. The U. S. Coast Guard has a research and development project to study the feasibility of solar power for aid to navigation buoys and shore aids. Fifty buoys, near Miami, Florida, have operated with solar panels for about one year. The panels recharge lead acid batteries which power lights. The panels, four or eight watt units, are sufficient to keep the batteries fully charged in the summer and 70 percent charged, under worst conditions, in the winter. Fifty new buoys, with eight or 16 watt panels, will be placed in service near Boston. The solar panels are supplied by Optical Coating Laboratory, Incorporated.

Automatic Power Incorporated supplies solar powered units for a number of marine uses, and have many units operating on fixed structures and buoys in the ocean. They believe that the environment of a SALM is too hostile for solar panels. The risk of damage (by mooring hawsers, workmen, or a ship riding onto the buoy) is very high. Moreover, secondary (recargeable) batteries are not suitable for use on a SALM. Automatic Power believes that primary batteries constitute the best power source for a SALM.

Since cable could be used with CALMs (section 4.4.3) power might be carried by the cable from the platform to the SPM. The fact that a CALM does not submerge makes the use of batteries simpler than for SALMs.

Other factors beside the source of energy are important to good power supply design. Large ground return conducters grounded to the hull/seawater at a single point can help prevent or reduce noise induced into signal circuits. Signal and transmission circuits must also be properly grounded. In this

and all other SPM mounted equipment, waterproofing is a must. Care must be taken with removable connectors. If any are used, service personnel must be properly instructed in the procedure for mating them to prevent corrosion and moisture on electrical contacts.

Since loss of power to SPM mounted components can cause total loss of the MLMS, and since service may not be possible during storms, a battery monitoring capability is often built into the system. The power supply (battery) voltage level is transmitted to the control room. This information, with the discharge curves, provides continuous information on the operating time remaining on the batteries. A low level indicator which transmits a signal when the battery voltage is less than a preset level would be simpler than transmitting the battery voltage continuously or at regular intervals. Unfortunately, battery discharge characteristics depend upon such things as load, duty cycle and temperature. A single data point (low level indicator) does not reliably indicate the operating time remaining on the batteries. With sufficient historical data on a particular installation, the low level indicator might be adequate. Long periods of battery-powered MLMS operation on SPMs has been attained.

4.5 DATA HANDLING SUBSYSTEM AND COMPONENTS

The size and configuration of the data handling subsystem is a direct function of the sophistication of the MLMS. For many configurations, immediate access to data acquired within the past hour is probably sufficient. For a MLMS with a more sophisticated warning subsystem and/or a prediction system immediate access to a larger data base is required. The requirements for such a data base are discussed in Sections 4.3.2, 5.3 and 6. When a predictional system is used, the data-handling subsystem may serve as an interface between the MLWS and the

MLPS. Data may be stored in a number of forms as described below.

4.5.1 Analog Data

Most existing mooring load monitoring systems use a chart recorder as the primary method of data display; therefore, a means of conveniently storing the charts is the only requirement of the data handling subsystem. An operator cannot reasonably be expected to make judgements on recordings of shock or impulse loads. He can follow trends in the peak loads to estimate future loading. Consequently, the recorder chart speed can be very slow. As an example, if one wished to display a 10-second period (or 1/10 cycles/sec) oscillation on 1/8 inch of chart, the required chart speed is 45 inches per hour. This further computes to 90 feet per day. This is not a recommendation of chart speeds (Figure 3-1 is a typical chart recording), but does illustrate the small volume of paper required for low frequency recording. The space required to store records of a year's operation at one SPM is not very large. It is reasonable to consider storing six months of chart records for four to six SPMs on the control platform. The time period for retaining recordings would depend on the expected use of the data. For example, the U.S.C.G. might wish to examine such records in the event of a breakout and/or oil spill. Data on hawser load history might become part of the data base, Section 4.3.2, and be retained indefinitely.

Analog data can be recorded on magnetic tape which is more useful for data analysis. This might be done as part of an R&D effort to provide better prediction and warning schemes. Magnetic tape recording is more expensive than paper chart recording, and requires more maintenance. In addition, magnetic tapes can be erased or garbled if not handled properly. Since an operating port is not likely to routinely collect data for

R&D, the provision of a magnetic tape interface, for R&D use, is probably adequate.

4.5.2 Digital Data

When it is likely that computer processing of stored data will be required, it is convenient to store data in digital form. A requirement to handle digital data will exist for any of the following cases:

1. The MLMS warning subsystem uses computer processing of measured load data.
2. The MLWS uses computer processing of measured data or a stored data base.
3. Data are to be collected for use in the development of items one and two.

In the first two cases, the data handling software could be, and probably should be, part of the required MLMS and MLWS programs. The last case is essentially a data acquisition or data logger requirement. There are many off-the-shelf systems which can perform this last function at a relatively low cost. If a larger computer were used for other purposes in the control room, it could perform this function with little or no increase in working memory. The main requirement is for permanent off-line storage.

Permanent storage for all three cases would probably be magnetic tape, disc or floppy disc. The amount of data to be stored and the operating environment make punched paper tape and cards unattractive.

Finally, all of the data to be handled and stored will probably not come from instrumentation. The operators may be required to enter data of various types, such as environmental data or weather predictions (see Section 5). Operator inputs could be via a normal computer terminal, data logger keyboard, or special keys on a control console. The data from instrumen-

tation, such as loads, wind, waves, etc. might be reduced before storage. Statistics of the data or histograms might be stored.

4.5.3 Video Storage

Video tape storage could be very useful when CRT data displays are used. Displays could be recorded for later examination or analysis. This is particularly useful when a large amount of data, acquired during demanding situations such as severe weather, are to be reviewed. However, video tape storage is redundant if digital data is stored.

4.6 WARNING SUBSYSTEM AND COMPONENTS

To ensure proper use by port personnel or the ship's master of a load monitoring or a load prediction system, the systems must have effective warning subsystems. Experience from comparable situations has shown that human surveillance of data displays alone is not adequate, particularly when personnel are on duty for more than a few hours (Brackner and McGrath, 1963).

A warning subsystem will consist of warning devices, (typically both aural and visual devices), a transmission link between control center and ship, a suitable logic, hardware and sorftware for activating the warning devices, and perhaps a means for deactivating warning signals. Warning devices will, typically, be installed at several locations. The warning devices must unequivocally direct attention either to the existence of a dangerous situation requiring immediate and decisive action or to a condition of imminent danger requiring great vigilance.

4.6.1 Decisive Action

Decisive action will generally be taken by the ship's master. He may take decisive action of his own volition and/or as a result of a recommendation of port personnel. Ideally, with a good data display and warning system, the master and port per-

sonnel would agree immediately on the proper response to a warning.

Decisive action based on mooring loads can take place in two steps. The first step is complete termination of cargo transfer operations and preparation for dropping of cargo hoses. The second step is dropping of cargo hoses and hawser and departure of the ship from the mooring. In some cases only the first step will be required while in other cases immediate execution of both steps will be required. Based on typical operating experience, the first step can be completed in a few minutes (say less than five) while both steps can be completed in about 20 minutes. Other actions, such as termination only of cargo pumping, are considered precautionary rather than decisive action.

4.6.2 Causes for Warnings and Decisive Actions

Four basic conditions should require issuance of a warning. These are, in order of decreasing severity or urgency:

1. An extremely high time rate of change of mooring load, signaling hawser failure or a system failure.
2. A measured peak load exceeding 80 to 90 percent of predetermined allowable load.
3. A short-term predicted load based on statistics of measured loads exceeding a predetermined allowable load.
4. A measured load reaching 60 to 70 percent of allowable load.

The first two conditions require decisive action, i.e., immediate termination of cargo transfer operations and a rapid decision on whether the ship should leave the mooring. The last two cases do not require decisive action but should act as a cue to appropriate port personnel and ship's master to review

load readouts, wind and wave conditions and ship yawing motions, to carry out available actions to reduce loads (steering or rudder, use of thrusters, etc.) and to alert cargo handling personnel to the situation. Some clear differentiation between the nature of these two situations is therefore needed in the warning system.

Statistics of measured response are considered much less useful than are peak values for direct triggering of an alarm. Statistical measures (RMS, significant, one-hundredth highest or 1/n'th highest) are only valid when sampled over a relatively long period (see Appendix D, Section D1). Such measures are most appropriate when used in a prediction scheme which can adequately relate peak values to relatively long term statistical values.

4.6.3 Types of Warning Devices

Warning devices are generally of the aural (auditory) and visual types. Specific types of devices which might be used in a mooring load monitoring system include:

1. Horns, whistles, bells, sirens and buzzers (aural)
2. Prerecorded verbal messages (aural)
3. Lights (visual)
4. Written console messages (visual).

These devices, whose characteristics and performance are discussed in Appendix C, can be used alone and in various combinations.

Horns, whistles, bells, sirens and loud buzzers are generally excellent attention-getting devices and generally have good ability to penetrate background noise. They are difficult, if not impossible, to ignore. They can indicate the need for action, but not the required type of action. It is feasible to provide two types of warnings by using steady and intermittent signals. Experience indicates that the use of more than two separate aural signals or devices can result in confusion.

Prerecorded verbal messages indicate specific action(s) required. If sufficiently loud, they can be effective attention-getting devices. State-of-the-art aircraft warning systems rely on a succinct, repeated message (Hunter, 1969). Succinct messages are clearly desirable. The message should be louder then ambient noise, but below the threshold of pain (about 90 db for the desired 500-400 Hz frequency range).

Lights are generally better suited as cueing devices than as prime attention-getters. They are, however, useful for directing attention, once gained, to a data display or a warning message (Dorfman and Golstein, 1971). They are also useful for maintaining attention after an aural device has been turned off. Color must be selected with care. Both visibility and human visual handicaps, as discussed in Appendix C, must be considered. Red is usually favored but other colors may provide better visibility under some conditions. The use of several warning lights of different colors can cause confusion.

Written message displays can be of the CRT or multiple-light type. CRT displays will probably be more compact for longer messages, but care must be taken, as described in Appendix C, to ensure good visibility. Light displays must be relatively large for good ledgibility, but avoid the complexity of color CRT displays. A single CRT display can be used for both data display and warning messages.

To avoid confusion, which defeats the purpose of a warning system, combinations of warning devices must be carefully chosen. Probably no more than one aural device should be used, even at the control center of a port handling two or more ships. This aural device directs attention to visual devices which specify the ship or ships causing the warning. Separate lights should be used for each ship if separate data displays are used for each ship (Dorfman and Goldstein, 1971).

4.6.4 Redundancy of Warning Devices

Experience with warning systems indicates that redundancy is a necessary feature of such systems. An appropriate system, as shown in Figure 4-8, provides redundancy through the use of both aural and visual devices (say horn and light) at both the control center and the ship. This is somewhat more complicated than those used in typical existing mooring load monitoring systems, which provide only an aural device on the ship. The use of two devices on the ship is necessary to provide for more than one type of warning. Care must be taken to ensure that essential voice communications can take place during an aural warning.

It is desirable that the visual warning consist of an attention-getting device (say a flashing light) which directs attention to a written message (say on a CRT display) which describes the reason for the warning and indicates required action.

It is not considered necessary or useful to provide warning devices on a SPM buoy. If warning devices are provided on the ship, the buoy location is redundant. Warning devices on the buoy are not considered a suitable alternative to a combination of warning devices and data displays, as proposed, on the ship.

4.6.5 Human-Warning System Interaction

Warning systems of load monitoring systems are designed to provoke human actions. In addition, existing load monitoring systems generally provide for human interaction with these warning systems through an ability of operating personnel to change the warning load level and to "accept", and hence defeat a warning by supressing the primary aural signal. Such interactions are acceptable only if the warning does not require decisive action.

Experience with aircraft cockpit warning systems, which are in many ways analogous to a mooring load warning system,

has shown that operating personnel cannot be permitted to modify, defeat or ignore warnings which require decisive action (Hunter, 1969). Based on available experience with warning systems, it is concluded that:

1. It must be sufficiently difficult to change warning load levels during normal operation of the load monitoring system.
2. When a warning requiring decisive action occurs, operating personnel must not be able to modify the warning to a point where it can be ignored, i.e., turning off a horn or siren.
3. When a warning occurs, which does not require decisive action, it should be possible under certain conditions to modify but not defeat the warning.

In the latter case, it is proposed that the aural, not the visual part of the warning, could be supressed, but only by agreement of and action by personnel at the control station and on the ship. Continued existence of the conditions which triggered the warning should, after a period of say five minutes, deactivate the aural part of the warning.

Termination of a warning is not straightforward, for cases when operating personnel are prohibited from affecting termination. Termination of cargo transfer,the crucial response to a warning, does not provide a ready mechanism, although a zero cargo transfer rate could be used to terminate the warning. A sustained zero measured load, which could be due to disconnection or failure of the hawser or MLMS failure, could be used to change the warning logic so that the warning could be more easily terminated. In the absence of these conditions, the aural warning could be terminated in the same manner as a nondecisive warning, but actual termination would only occur five minutes after the

last condition requiring a warning. It should also be possible, although intentionally difficult, for personnel at the control center to supress the warning subsystem in cases of malfunction which cause spurious warnings.

4.7 DISPLAY SUBSYSTEM AND COMPONENTS

The display subsystem provides a man/machine interface in a MLMS. Human factors, therefore, play an important role in its design. The first consideration is the functions the display must serve. Its primary purpose is to provide a convenient means of monitoring mooring loads. Other typical functions are to provide more specific information about problems or malfunctions when an alarm occurs and to provide a permanent record of load history and warnings.

Section 4.6 discussed methods for directing operator attention to a specific display after an alarm has sounded. At a multiple SPM port it is essential that display messages be unambiguous and be visible at the largest possible distance and viewing angle. The following are candidate displays for DWP use:

1. Meters and Lighted Bar Charts
2. Strip Chart Recorders
3. Cathode Ray Tube (CRT) Displays and Terminals
4. Digital Printers

They will be discussed individually in the following sections.

4.7.1 Meters and Lighted Bar Charts

There are many types of meters with a wide variety of scales and indicators. Analog meters usually have a rotating or sliding mechanical or light pointer. More recently light emitting diodes and similar devices have been used to make lighted bar type meters. A meter display of the instantaneous value of load is of little value since it must continuously be monitored to get useful information. Such devices could be

used to display load statistics, or peak loads for a given period. A lighted bar or a digital meter would be the best choice for viewing from a distance.

4.7.2 Strip Chart Recorders

Most existing MLMSs use a strip chart recorder for the display. A great deal of information is contained in a recording. When an alarm occurs, the operator can immediately see the magnitude of the peak load, the time of occurrence, and the variation of loads preceding this peak load. A one-hour record requires a relatively short chart; therefore, load trends can be quickly determined. This trend information greatly assists decision-making. The operator can perform the load prediction function in a system which uses a chart recorder display.

In the past, chart recorders have had one major flaw. The writing mechanism (pen) required frequent attention to keep it functioning properly. Ink pens tend to leak or become clogged. Heat styli were difficult to keep adjusted without burning the paper. Pressure sensitive paper worked rather well but became scratched and marked easily when the charts were reviewed. In the past few years improvements (such as cartridge pens and better special paper) have been made, and acceptable writing mechanisms are available.

4.7.3 CRT Displays and Terminals

A Cathode Ray Tube display can be used for two types of displays. The first type is an oscilloscope to display instantaneous loads in the same manner as a chart recorder. Recent load history could be displayed on a storage oscilloscope with permanent storage of load history on magnetic tape. Several factors such as cost and care of storing magnetic tape make use of a chart recorder more attractive in the control room; however, a small, lightweight oscilloscope might be carried

aboard ship as a remote display. Frames or fixed period records of the load could be transmitted from the control room to the ship to display the most recent load history or, on request, previous frames of load history. In addition, the predicted peak load could be displayed on the oscilloscope in digital form.

The CRT terminal is perhaps more familiar to computer and process control operators. It could be used in a MLMS to display printed warning messages, bar charts or graphics such as a port diagram. A color diagram of the platform and SPMs could display a large amount of information in a small area. The color of the SPM symbol could represent normal or high loads. This might be supplemented with printed messages. Section 4.6 discusses the impact of factors on the selection and use of such displays. The use of colors is discussed in Appendix A.

4.7.4 Digital Printers

Digital printers and plotters could be used to display the same information as a CRT terminal. A plotter is not a cost-effective or practical display for MLMS use; however, printed alpha-numeric messages are very useful. One advantage is that a permanent record is made. A disadvantage is that printed messages generally cannot be seen well from a distance. This would give it a low rating as a warning display device.

All display devices are compared and rated for DWP use in Section 5.

4.8 GENERAL SPECIFICATIONS FOR MLMS, SUBSYSTEMS AND COMPONENTS

Detailed specifications for a MLMS can only be developed when the deepwater port configuration and requirements are known. The specifications in this section are, therefore, general and are intended to be applicable to any probable U. S. DWP. Overall system specifications are:

Effectiveness: The overall system must be capable of making load measurements, displaying results and sounding unambiguous alarms. It must operate with a specified accuracy and a known and acceptable reliability.

Accuracy: The overall system accuracy should be $\pm$ 5 percent or better. This includes the combined accuracies of measurement, transmission, display and alarms, as well as all effects of temperature, humidity, hysteresis and non-linearities. After operational experience has been gained and calibration and maintenance procedures have been refined, this figure can probably be improved. Existing system descriptions quote sensor accuracies of $\pm$ 1 percent, but no overall system accuracies are specified.

Frequency Response: Hardware is available to provide a system frequency response greater than that required for mooring load measurements and predictions. Data sampling rates and other factors can limit frequency response, and, therefore, must be carefully considered. Shock loads can cause significant reduction in hawser breaking strength as described in Section 8.3, and it is therefore recommended that the MLMS have a sufficiently high frequency response to determine maximum hawser loading rates. A frequency response of one-half Hertz is considered desirable and is the recommended overall system frequency response, even though this frequency is higher than the maximum expected wave frequency (0.25 to 0.35 Hertz). The higher frequency response ensures accurate determination of peak loads and peak loading rates. If a data sampling system is used, the sampling rate will be determined by this frequency response.

Reliability: The reliability and availability required of a MLMS will depend on the approach adopted by the DWP. It may be reasonable to require that the MLMS be operational before a ship is allowed to moor and if it fails, cargo transfer must stop and perhaps the ship leave the mooring. This policy has been adopted by the operators of at least one facility. If this policy is adopted, the port operator working with the MLMS supplier will determine an acceptable system reliability and availability consistent with the costs of port closing due to MLMS failure.

The regulatory approach of requiring the MLMS to be operative has important advantages. Detailed monitoring of MLMS specification, design and equipment testing is not required. Also the reliability and availability tends to be self-correcting since, if the availability is low, the port operator will have very strong economic incentive to improve the system. This approach to MLMS reliability and availability does require that periodic inspections be made to ensure that in fact the operating policy is being followed.

The actual reliability and availability of MLMS at existing SPM installations could not be documented since accurate records are not kept. However, one operator reported availability amounted to about one day of outage per year. There is no inherent reason why very high reliability and availability cannot be obtained and, in fact, seem to have been obtained with well-designed systems. Thus, the requirement that the MLMS be operative should not impose an unacceptable operational limitation.

Inspection and Maintenance: These parameters are best

specified for the individual subsystems and components; however, total system inspection and routine maintenance requirements must be minimized to keep operating costs within reason. Existing systems using batteries on the buoy typically require battery replacement at three to six month intervals. These are reasonable periods for on-buoy maintenance and inspection.

Cost: Typical load monitoring systems with shear pin sensors, radio or acoustic links to ship, chart recorders, alarms and rechargeable batteries cost:

CALM $30,000 - $40,000 (Radio Link)
$200,000 with measurement of environmental data.

SALM $100,000 (Acoustic Link)

With SALMs the cost will increase with increasing transmission distance. For distances of more than, say, one-half mile, an acoustic relay buoy or more probably an acoustic link - cable system will be required. Underwater cable systems will probably cost two to three dollars per foot plus installation costs. Installation costs for buried cables will probably be acceptable only if the MLMS cables can be buried with other cables or pipes between the buoy and the PCP. Systems for alongside moorings with 20 mooring hooks cost, typically, $100,000 to $150,000. The addition of a sophisticated data processing/display/storage system such as that being supplied by Interstate Electronics Corporation for the Exxon Honda facility will probably add $30,000 to $40,000 to the cost of a MLMS.

4.8.1 Load Measurement Subsystem Specifications

The specifications for the load measurement subsystem are generally more stingent that those for any other subsystem. Some general specifications are given in Table 4-3, including specifications for the individual components where applicable.

4.8.2 Data-Handling Subsystem Specifications

The specifications of a data-handling subsystem are determined by the requirements of the load warning subsystem and the MLPS which are discussed in Sections 4.8.3 and 6. Since suitable data processing hardware is readily available from many sources, detailed equipment specifications are not given here.

4.8.3 Load Warning Subsystem Specifications

The primary requirement for the warning subsystem is adequacy of alarms. The aural and visual warning devices must have signal characteristics (intensity, frequency, color, etc.) which permit them to be heard and seen at all times in the ambient environment (control center, ship's bridge, etc.), as described in Section 4.6 and Appendix C. These devices can and should have a very high reliability (say at least one year mean time between failure) and a minimum down time (say four hours mean time to repair). Means must be provided for checking the operability of all warning devices and repairs, when required, should be made.

4.8.4 Data Display Subsystem Specifications

The data display subsystem must be an effective interface between the MLMS and port personnel and/or the ship's master. Subsystem specifications are given below and individual component specifications are listed in Table 4-4.

Accuracy: In general display component accuracies are better than measurement component accuracies and there-

fore contribute very little to system errors. Typical component accuracies vary from .001 percent to 3 percent.

Frequency Response: Display subsystem components, except for strip chart recorders and mechanical meter movements, have response characteristics much better than that required for MLMS use. Since chart recorders and meters are not likely to be used for determining shock loads, their frequency response characteristics are of minor concern.

Reliability: Display subsystem components are critical for proper MLMS operation and must be very reliable. Redundancy of displays increases reliability and is desirable for other reasons (see Section 4.6.3). Many display components are available which have sufficient reliability for control room use. Components for shipboard use must meet more stringent specifications and may be more difficult, but not impossible, to obtain.

Inspection and Maintenance: The display subsystem is accessible to personnel at all times; therefore, inspection and maintenance of components, per manufacturer's recommendations, should be no problem. It is necessary to periodically (1 to 6 months, depending on component type) check the calibration of these components to ensure that system accuracy is maintained.

Location: A display subsystem is required in the control room. It is recommended that display components also be located on the ship's bridge.

Adaptability: The display subsystem design should be flexible so that it can be easily up-graded when system improvements, such as improved prediction techniques, are made.

Size and Weight: Neither the size nor weight of components located in the control room are critical; however, components carried aboard ship must be very small and lightweight. Such components are available.

Cost: The cost of the display subsystem is not a large part of the MLMS cost. Component costs can range from \$50 for a simple meter to \$1500 for a good portable oscilloscope.

It is possible to have a good display subsystem both in the control room and on the ship.

TABLE 4-1

TYPICAL COMMERCIAL BATTERY TYPES AND REPRESENTATIVE CHARACTERISTICS

	TYPE	ANODES	CATHODE	ELECTROLYTE	OPERATING TEMPERATURE °F	CAPACITY AMPERE-HOURS	wh/lb.	wh/cu. in.	RELATIVE COST
1.	Air Cell	Zn	O_2/C	NaOH	-20 - 100	1000	90	4	1
2.	Dry Cell	Zn	MnO_2/C	$NH_4Cl/ZnCl_2$	0 - 100	5	26	1.8	3
3.	Alkaline	Zn	MnO_2/C	KOH	-40 - 120	20	30	3.5	5
4.	R.M. Mercury	Zn	HgO/Fe	KOH	40 - 165	14	35	3.3	10
5.	Silver	Zn	Ag_2O/Fe	NaOH	-20 - 100	0.1	75	6	24
6.	Mg-AgCl	Mg	AgCl/Ag	$MgCl_2$	-50 - 65	20	20	8.5	9
7.	$Mg-CuCl_2$	Mg	$CuCl_2/Cu$	$MgCl_2$	-50 - 65	20	20	8.5	8

Notes: 1. wh/lb. - Energy density in watt hours per pound

2. wh/cu. in. - Energy density in watt hours per cubic inch

3. Relative Cost - Approximate ratio of battery type cost to air cell cost

TABLE 4-2

TYPICAL COMMERCIAL SECONDARY (REVERSIBLE SYSTEM) BATTERIES

TYPE	wh/lb.	wh/cu. in.	ESTIMATED CYCLE LIFE	COST RANGE	CHARGING TIME HRS.
1. Lead-Acid Industrial	13.1	1.35	1600	Low	5-10
2. Automotive	15	1.3	300	Low	5-10
3. Nickel-cadmium pocket	11	0.6	2000	Medium	7-8
a) Sintered	11.5	0.88	3000	High	2 Vented 10 Sealed
4. Nickel Iron	10.6	0.92	2000	Low	6-7
5. Zinc-Silver	90	3.0	200	Highest	4-20

Notes:
1. wh/lb. - Energy density in watt hours per pound
2. wh/cu. in. - Energy density in watt hours per cubic inch
3. Costs for approximately equivalent 12 volt units:
   Low - under $100
   Medium - $100 to $300
   High - $300 to $500
   Highest - Over $500

TABLE 4-3

LOAD MEASUREMENT SUBSYSTEM SPECIFICATIONS

COMPONENT SPECIFICATION	VALUE	UNITS	COMMENTS
1. Sensor			
a. Accuracy	± 1	Percent	Includes effects of temperature, humidity, hysteresis and non-linearities. Typical existing units are specified ± 1 to ± 2 percent
b. Reliability			This is a critical component; therefore, reliability must be sufficient to ensure MLMS reliability.
c. Inspection			Each time SPM is serviced, inspect for physical damage, wear, corrosion, biofouling, and loss of waterproofing of cable or connectors.
d. Calibration			In situ check of calibration (low loads only) should be possible using a service boat (or tug) with a calibrated load cell to apply load.
e. Maintenance			Cleaning, emphasis on freedom from mechanical restriction, and repairs as required.
f. Weight	100	lbs. max.	Present units weigh less than 100 lbs. This should be upper limit for sensors which are not mounted on mooring components.
2. Transmission Equipment			
a. Accuracy	±1	Percent	All errors introduced in signal transmission must be of this order (±1 percent worst cause) if MLMS accuracy of ±5 percent is to be achieved.
b. Reliability			Same as Item 1.b.
c. Inspection			Each time SPM is serviced, inspect for physical damage, corrosion, loss of waterproofing, etc. If radio is used, port operator must ensure conformance to all applicable FCC regulations.
d. Maintenance			Periodic (once or twice a year) alignment of transmitters and receivers (radio and/or acoustic) may be required.

TABLE 4-4

DATA DISPLAY SUBSYSTEM SPECIFICATIONS

ITEM SPECIFICATION	VALUE	UNITS	COMMENTS
1. Analog Displays			
a. Accuracy	$\pm\frac{1}{2}$	Percent in control room	All display devices must have accuracy of this order if MLMS accuracy of ± 5 percent is to be achieved.
	± 3	Percent on ship	
b. Response	10	Second	For response to full scale input step (more critical on chart recorders than meters). Most good recorders have response times on the order of 1 second.
c. Reliability			This is a critical component; therefore reliability must be sufficient to ensure specified MLMS reliability.
d. Calibration			Calibration separate from system calibration (Table 4-4, 1.d. calibrates system). Can and should be done on a regular schedule.
e. Maintenance			Display components of the type required are generally low maintenance items.
2. Digital and Message Displays			
a. Accuracy			Digital displays and meters are generally much more accurate than analog devices and therefore, contribute very little to system errors.
b. Visibility			Visibility is very important. Selected devices must be visible over the entire range of an operator's normal working area.
c. Reliability			Same as 1.d.
d. Maintenance			Same as 1.e.

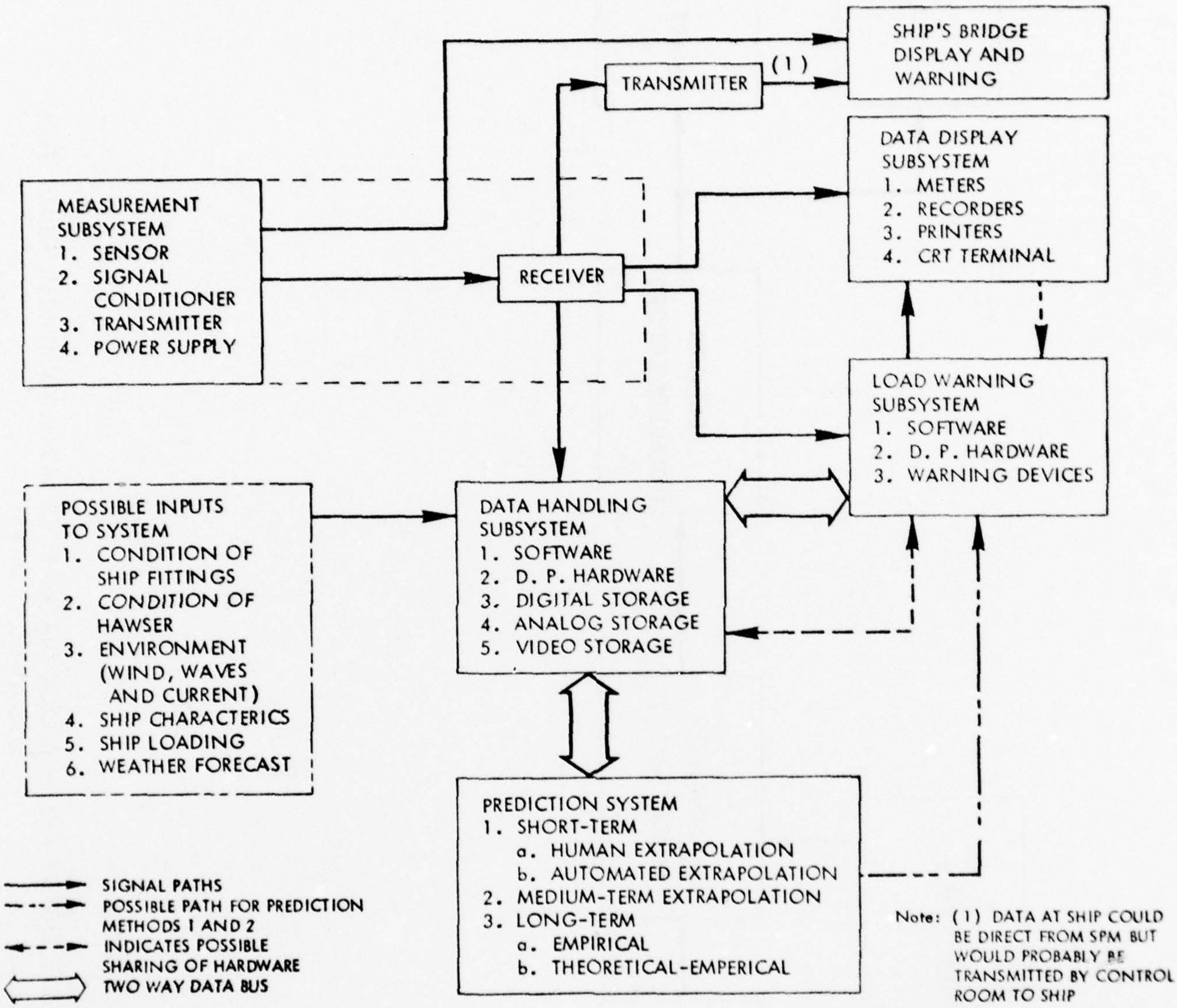


FIGURE 4-1 - BLOCK DIAGRAM OF GENERAL MOORING LOAD MONITORING AND PREDICTION SYSTEMS

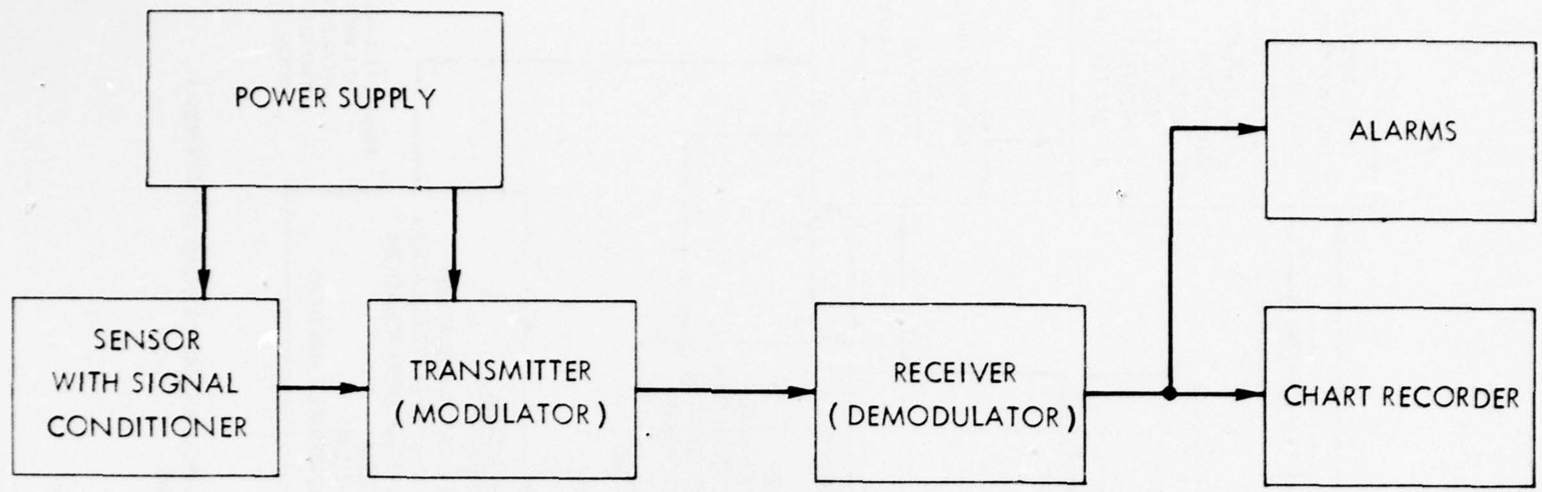


FIGURE 4-2 - BLOCK DIAGRAM OF MINIMUM USEFUL MLMS FOR USE AT U. S. DWPS

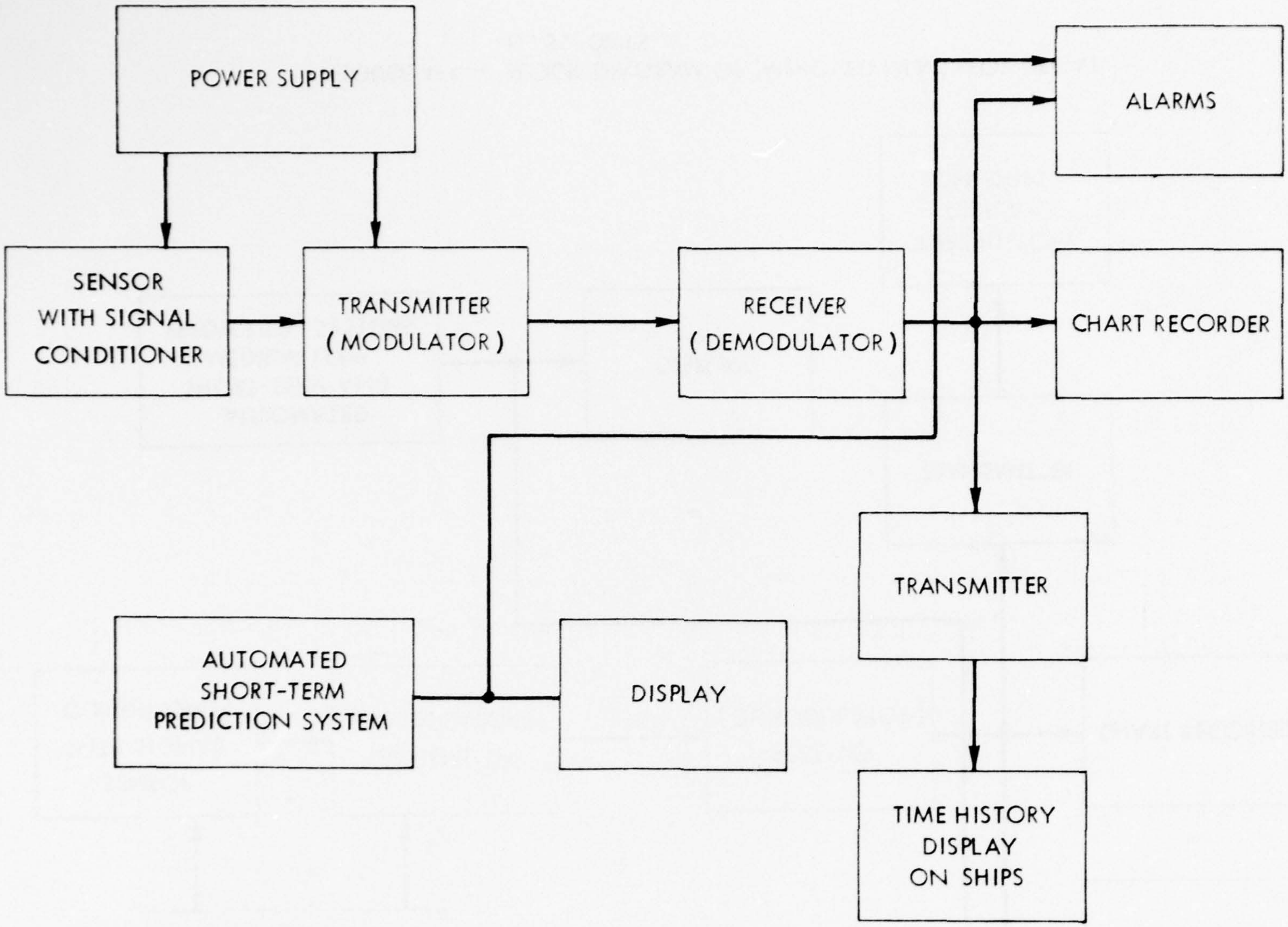


FIGURE 4-3 - BLOCK DIAGRAM OF RECOMMENDED MLMS FOR INITAL USE AT U. S. DWPS

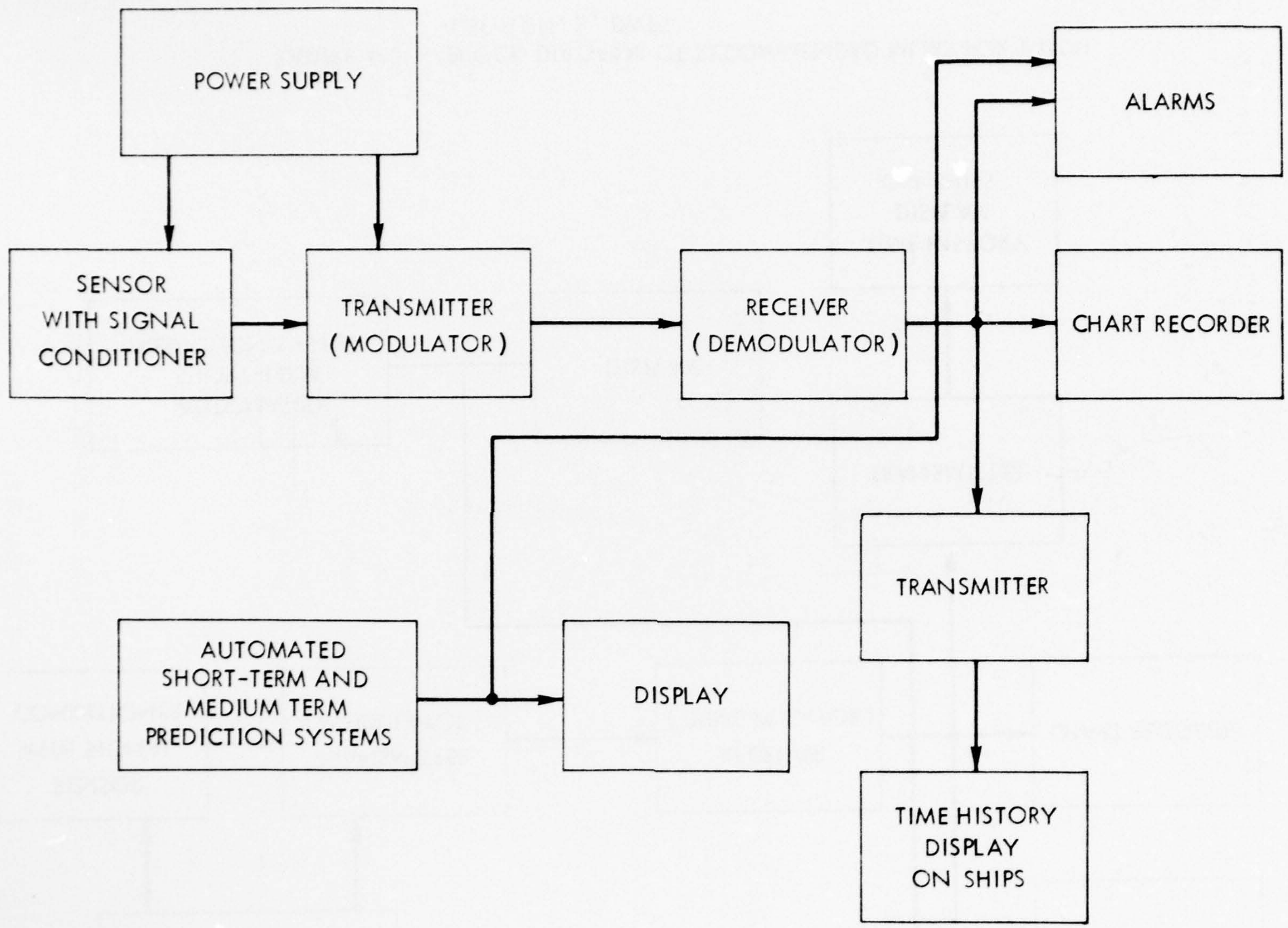


FIGURE 4-4 - BLOCK DIAGRAM OF IMPROVED MLMS FOR USE AT U.S. DWPS

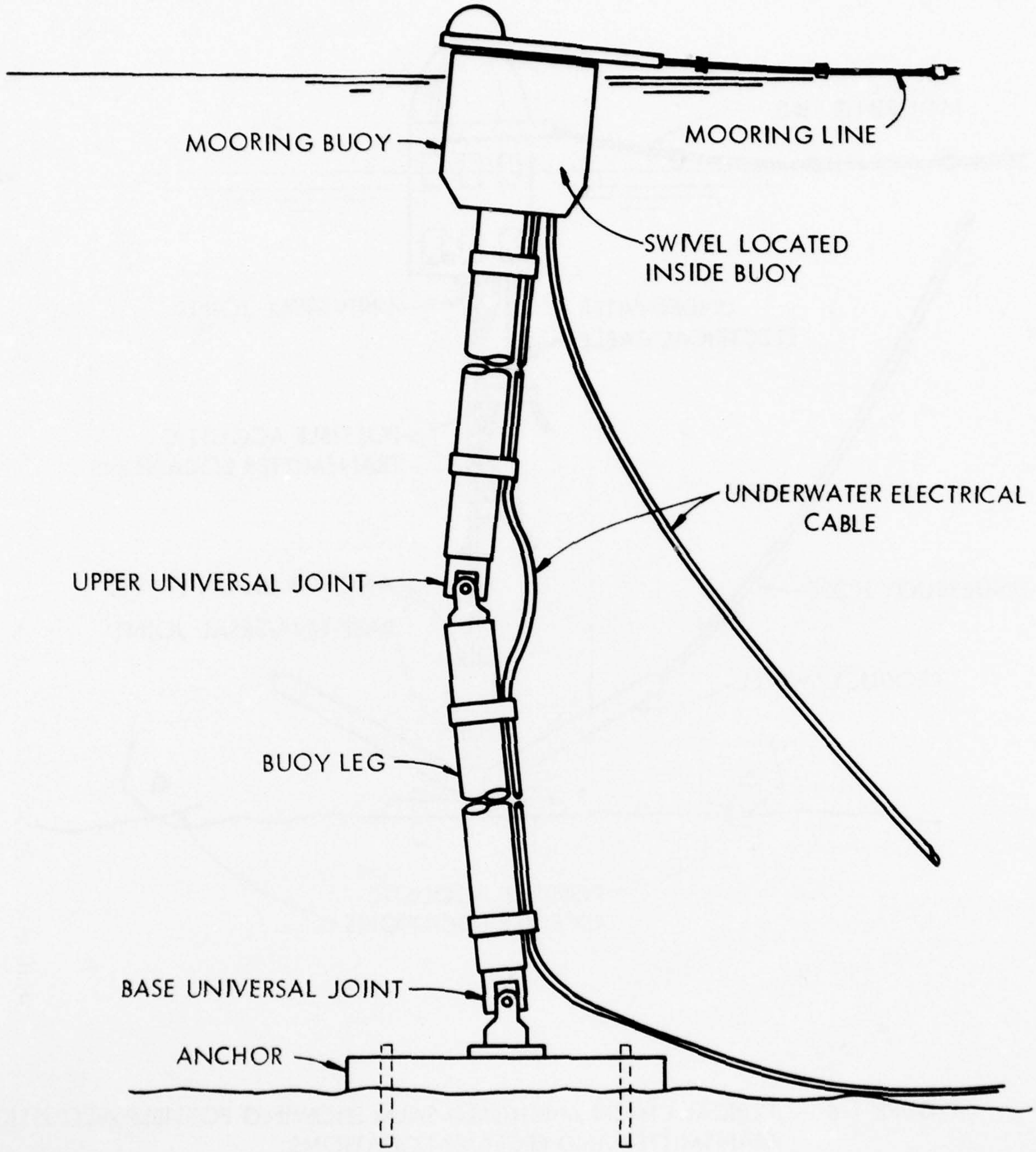


FIGURE 4-5 - TYPICAL SALM WITH RISER SHOWING POSSIBLE ELECTRICAL CABLE LOCATIONS

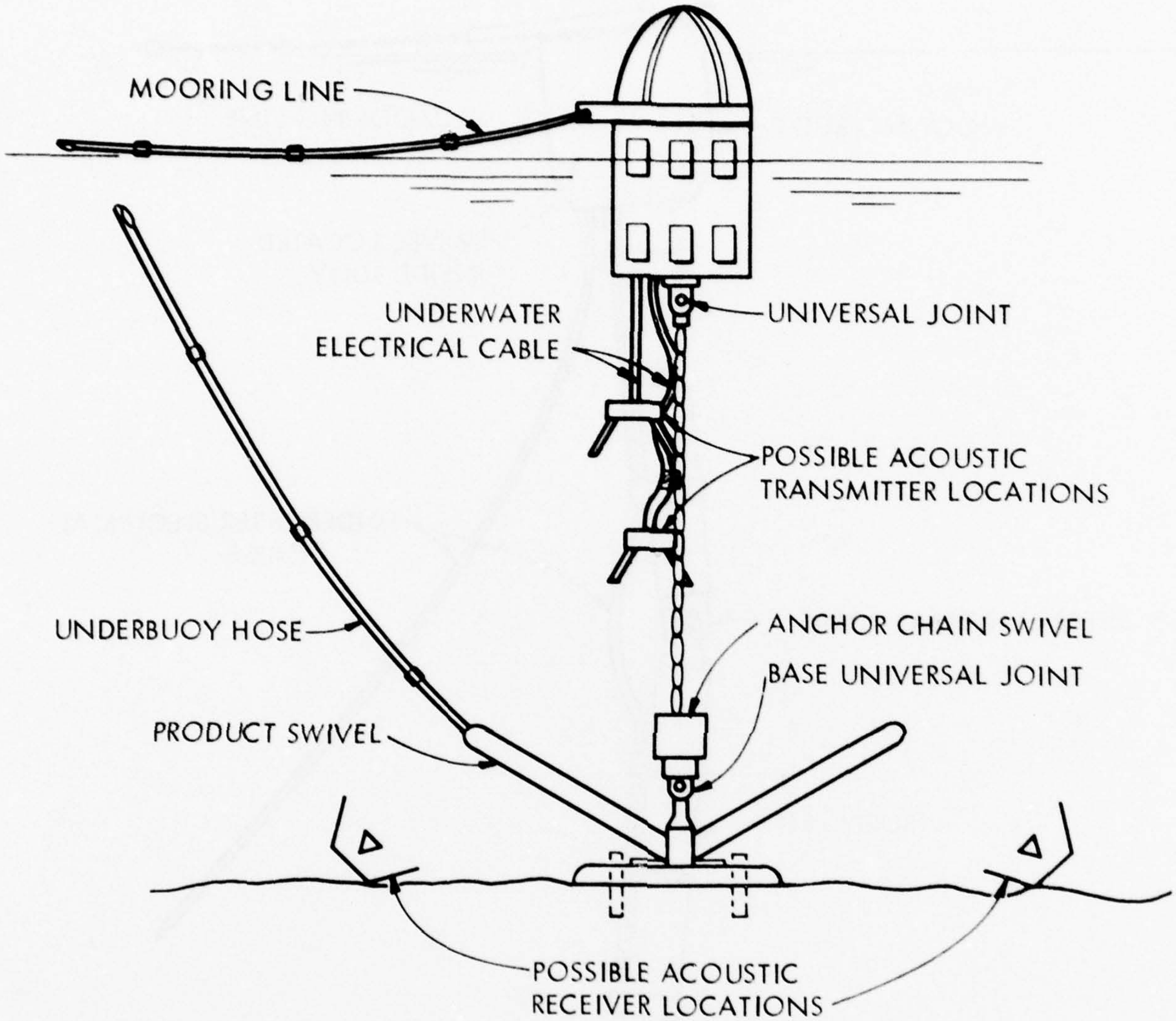
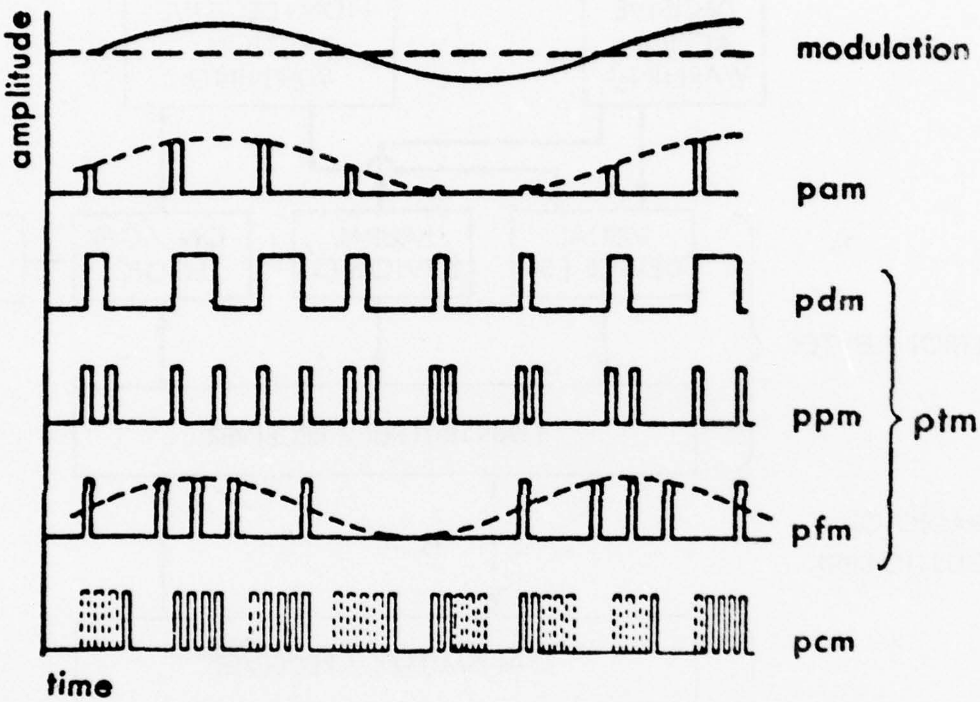


FIGURE 4-6 - TYPICAL CHAIN ANCHORED SALM SHOWING POSSIBLE ACOUSTIC TRANSMITTER AND RECEIVER LOCATIONS



NOTES:

pam - PULSE AMPLITUDE MODULATION
pcm - PULSE CODE MODULATION
pdm - PULSE DURATION MODULATION
pfm - PULSE FREQUENCY MODULATION
ppm - PULSE POSITION MODULATION

FIGURE 4-7 - PULSE MODULATION METHODS

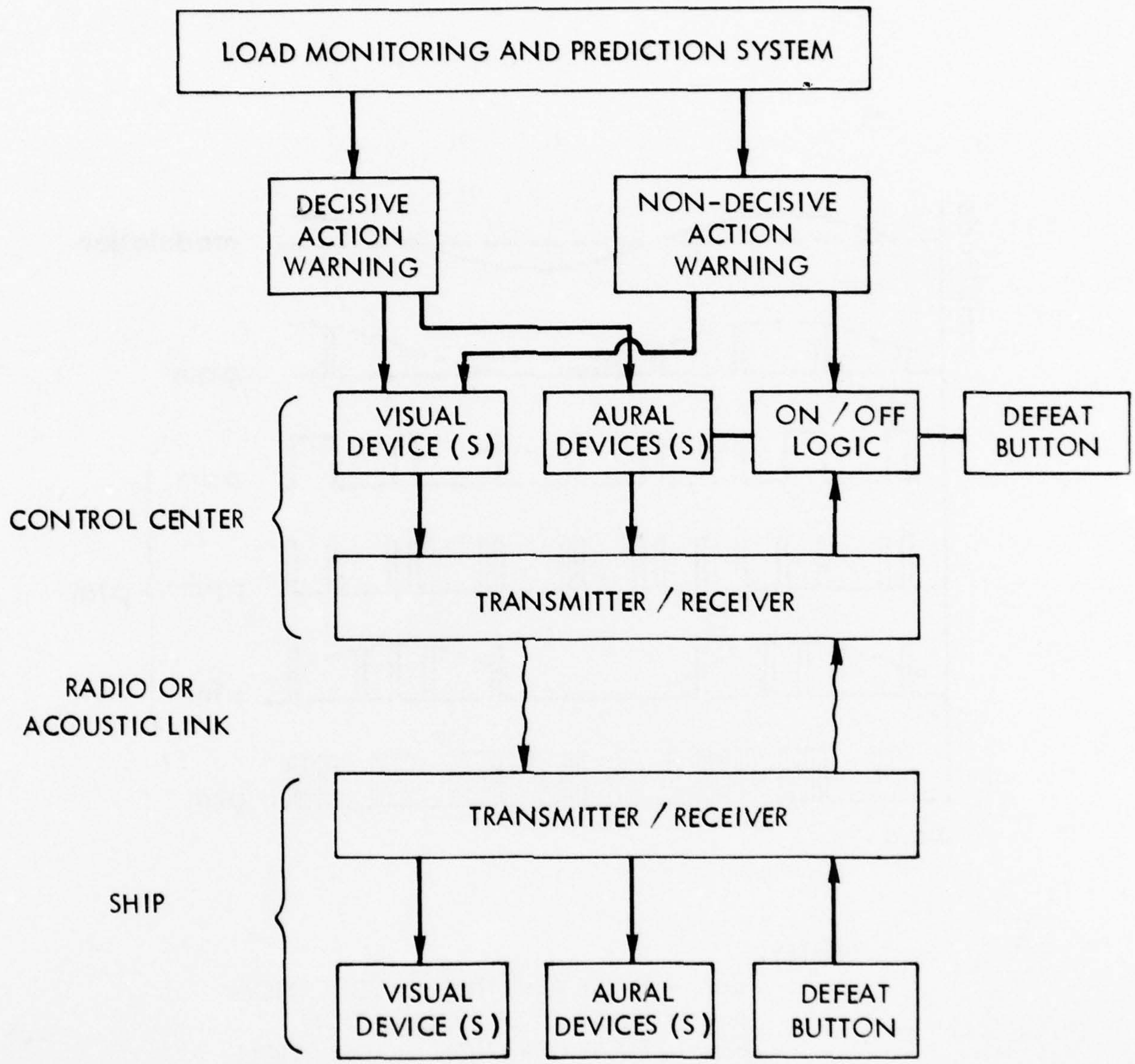


FIGURE 4-8 - BLOCK DIAGRAM OF TYPICAL WARNING SYSTEM USING RADIO LINK, WITH TWO TYPES OF WARNINGS AND A SCHEME FOR PARTIAL DEFEAT OF AURAL DEVICE (S)

SECTION 5

CRITICAL COMPARISON OF MOORING LOAD MONITORING SYSTEMS

5.1 INTRODUCTION

In previous sections, existing and possible mooring load monitoring systems were described. The subsystems and components were defined, and in general terms, specified. In this section methods and components are critically compared and, when practical, listed in a preferential order.

Any rating scheme for an arbitrary MLMS (i.e., one not designed for a specific DWP) must be largely qualitative. For each subsystem and component certain ranking factors, which will differ for different elements, will be of greatest importance. Consequently, each subsystem or component is ranked using only those of the following factors which are significant:

1. Accuracy
2. Reliability
3. Location
4. Inspection Criteria
5. Maintenance Requirements
6. Adaptability - Potential for Upgrading
7. Size and Weight
8. Costs - Capital and Operating

These factors were discussed in the specifications of Section 4.8. They are discussed in this section only where necessary.

5.2 LOAD MEASUREMENT SUBSYSTEM

This subsystem is ranked according to the possible installation locations in Table 5-1. In most cases the sensor location is the determining factor.

The various types of sensors are ranked in Table 5-2. The signal conditioners are included in the table because they must be compatible with the sensor and are often located within the sensor.

The different types of transmission links are rated in Table 5-3. Since the type of SPM determines transmission link suitability, Table 5-3 ranks transmission links separately for CALM or tower and SALM use.

5.3 DATA HANDLING SUBSYSTEM

The requirements of the data handling subsystem are determined by the load warning subsystem and load prediction system. Consequently only the components are rated. Both analog and digital data handling equipment are rated in Table 5-4.

5.4 LOAD WARNING SUBSYSTEM

The warning device is the primary component of any warning subsystem, and the type(s) and location(s) of these devices define the warning subsystem. Table 5-5 presents a comparison and ranking of warning devices. Table 5-6 presents rankings of combinations of devices, based on the need for such combinations, as established in Section 4.5. Other components of the subsystem, such as data handling and transmission components, will be shared with other subsystems and are evaluated elsewhere in this section.

5.5 DATA DISPLAY SUBSYSTEM

The data display subsystem must accurately display data, warnings and perhaps messages. Displays are required in the control room of a DWP and are recommended for use on the ships bridge. Display components are listed in Table 5-7 and ranked for use in the control room and on the ship.

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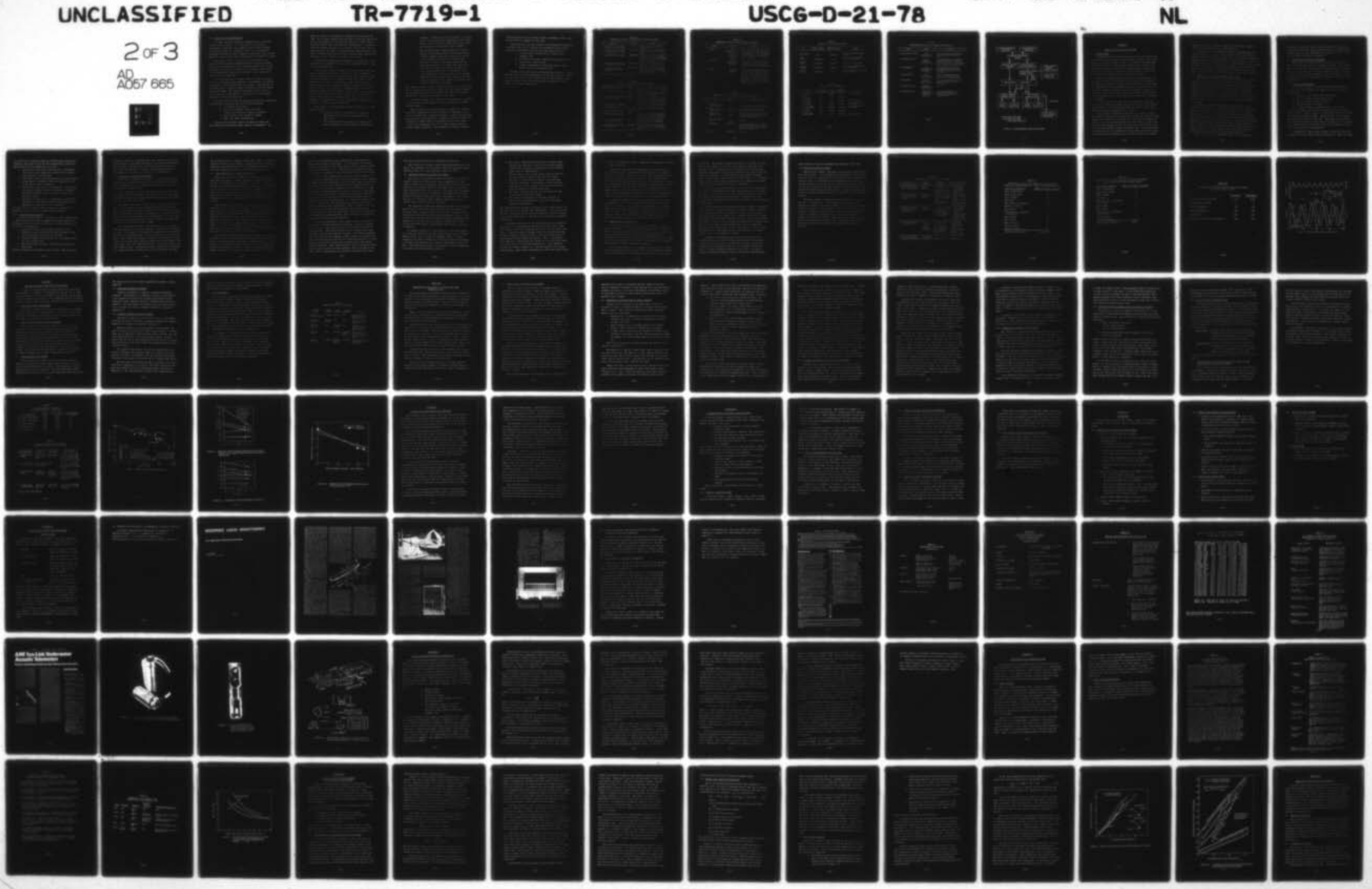
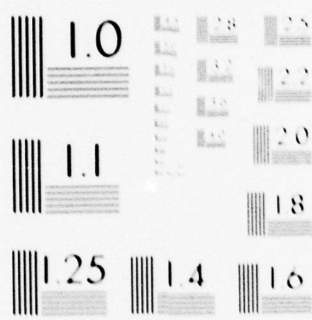




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

5.6 SUMMARY AND RECOMMENDATIONS

All MLMS subsystems and major components are listed and ranked in this section. It is possible to select only subsystems, components, and locations with a "Good" ranking for CALM and tower use. However, there is no transmission equipment which has a "Good" ranking for SALM use. This clearly identifies an area where more research and development is needed.

The tables of this section and the specifications of Section 4.8 are used to recommend specific subsystem configurations including hardware and operating methods. This is the information necessary to complete the definition of the three MLMS configurations described in Section 4.3 and depicted in Figures 4-2, 4-3, and 4-4.

It is not practical to require that all ships which moor at a U. S. DWP carry MLMS components. Furthermore, the amount of equipment carried aboard must be minimum. Consequently, the load measurement subsystem should be located on the SPM rather than on the ship. The preferred location for the sensor is at the buoy end of the hawser. At present, the strain gaged shear pin is the preferred sensor.

For CALM and Tower SPMs the preferred measurement subsystem, using present technology, has the following features:

1. Is located on the buoy.
2. Uses a strain gaged load sensor with a built-in solid-state signal conditioner.
3. Uses FM radio, with analog or sampled data, for signal transmission.

The first two features remain the same for SALMs, but radio cannot be used except under special circumstances. An

acoustic device is recommended to transmit the data from the SPM. If a receiver mounted near the base of the buoy can be protected from damage, it can feed the signal to a cable (buried with the control cable) that goes to the platform. If the area directly beneath the buoy is too hostile, the receiver can be located beyond the range of ship movements, approximately a half mile. From this point to the control platform any transmission technique (radio, acoustic, or cable) can be used.

No specific data handling subsystem is recommended. There are many good components to choose from depending on other data processing requirements.

Based on the ratings in Tables 5-5 and 5-6 and on factors, such as redundancy, discussed in Section 4.6, a recommended basic warning subsystem has been defined. This subsystem, which is based on Figure 4-5, is shown in Figure 5-1. Basic logic and data processing is accomplished at the control center. A portable unit containing data displays and warnings is carried onto the ship by port personnel. Multiplexing of the transmission to provide two data channels plus voice link is required between the ship and the control center, one for the warning device signal and one for warning signal supression. In general, it is proposed to use the same warning subsystem for all types of SPM's and port facilities.

Some features of the warning subsystem of Figure 5-1 worth noting include:

1. The aural alarm is continuous for situations requiring decisive action, intermittent for other cases.
2. The intermittent aural alarm can be turned off only by appropriate action taken at all warning

stations. Visual devices will continue to operate for a fixed period after termination of the aural device. If no action is taken, both devices will go off after a fixed period, say 10 minutes.

3. The continuous aural warning cannot be readily turned off, although a means for turning off the complete warning subsystem in cases of a malfunction, should be provided. It would become possible to turn off the aural warning by the same means described in 2 above with the existence for some fixed period (say one minute) of zero cargo transfer rate or zero hawser load. If an appropriate action is taken at all warning stations, the warning would be cancelled at some period, say three to five minutes, after the last condition requiring a warning.

This approach, which is more complex than those now in use, will almost certainly meet with resistance from operating personnel who will want to have the ability to turn off, at will, any aural alarm. This pressure should be resisted.

As noted in Figure 5-1, portable radio transceivers carried on the ship by port personnel, if used, should have an aural warning device.

The recommended system must provice a number of elements including: warning devices and transmission equipment as described; hardware and software necessary to convert measured and predicted peak loads and rate of change of load into steady or intermediate input signals to warning devices; and a logic circuit for terminating some or all input signals based on various inputs described. The hardware and software would be

located primarily at the control center, although a simple logic circuit would be required on the ship.

Using Table 5-7 and the criteria of choosing only components or methods with "Good" ranking, the recommended data display subsystem configuration has the following characteristics:

1. A strip chart recorder will be used in the control room.
2. A CRT terminal and/or digital meters may also be used in the control room.
3. A small lightweight oscilloscope and/or digital meters will be used aboard ship.

Mooring load measurements, with appropriate warning criteria, provide a powerful decision-making tool for DWP operators. This is especially true if other factors such as environmental data, weater forecasts and condition of ship's fittings have been taken into account (Figure 4-1).

TABLE 5-1

PREFERENTIAL LISTING OF LOAD MEASUREMENT SUBSYSTEM LOCATIONS

Location	Ranking	Comments
1. Equipment on SPM, sensor in end of hawser assembly.	Good	Considerable experience with existing systems.
2. Equipment on SPM, sensor attached to load bearing member of SPM.	Acceptable	Has been done. See Section 4.4.1 for discussion of possible inaccuracies.
3. Equipment on Ship, sensor at end of hawser assembly	Acceptable (Qualified)	Depends on whether the sensor must be carried aboard or can remain installed in the hawser assembly. Has worked well on dedicated ships where sensor remains on board (in chain stopper, winch, etc.).
4. Transducers permanently mounted in or on the rope.	Unacceptable	Not possible at present; see Section 4.4.1. Development may be possible in the future.
5. Sensor(s) mounted in anchor leg(s) to ocean bottom.	Unacceptable	Unacceptable as a substitute for hawser load measurement, and not deemed necessary as redundant or primary measurement.

TABLE 5-2

PREFERENTIAL LISTING OF SENSORS AND SIGNAL CONDITIONERS

Sensor/Signal Conditioner Type	*Ranking*	*Comments*
1. Shear Pin - Strain Gaged.	Good	This is now the preferred sensor for existing systems.
2. Tensile Link - Strain Gaged.	Good (Qualified)	Performance comparable to that of shear pin, but size and weight (see Section 4.8.1) make it much less attractive.
3. Load Cell attached to SPM load bearing member - Strain Gaged.	Good (Qualified)	The load cell itself may be good but the location may not be the best.
4. Load Cell with LVDT	Good (Qualified)	This type is used at Anglesea (see Section 3.2): however, more experience is needed. One U. S. manufacturer was skeptical of LVDT use in the ocean environment.
5. Load Cells with other types of transducers (see Section 4.4.1 and Appendix B-1).	-	None known. Other types are possible and may be considered in the future, but cost of R&D must be considered.
6. Acoustic transducers in rope.	Unacceptable	Not feasible at present, but R&D could change the prospects (see Section 4.4.1).
7. Temperature transducers in rope.	Unacceptable	Same as 6.
8. Signal Conditioner - Solid State with direct FM output.	Good	Solid state units, incorporated into the sensor, which give a variable frequency output are probably the best possible for this application (example resistance to frequency conversion for strain gages).
9. Signal Conditioner - Solid State with analog output.	Good	This can be as good as the above type especially if it drives a VCO (voltage controlled oscillator) to provide FM for transmission.
10. Signal Conditioner - Vacuum Tube of any type.	Unacceptable	Many factors make vacuum tubes unacceptable including environment, maintenance, reliability, size, weight and power consumption.

TABLE 5-3

PREFERENTIAL LISTING OF SIGNAL TRANSMISSION EQUIPMENT

Type	Ranking	Comments
1. Radio	Good (CALM and Tower) Acceptable (on Ship) Unacceptable (SALM)	Has been used very effectively on CALMS. On ships location of antenna may be a problem because many different types of ships may moor. Submerging of SALM would cause antenna damage and temporary or permanent loss of signal.
2. Acoustics	Acceptable (on all SPMs but doubtful from ships)	Ambient acoustic noise levels at a DWP may be a serious problem and needs further investigation. Problem for transmission to and from ship when ship draft approaches water depth.
3. Cable	Acceptable in special cases	In very deep water cable can be used with CALMS, towers and some types of SALMs. If special equipment were developed to pass signal across the swival, a cable could be used with chain anchored SALMs in shallow water. The ranking of such a cable system would be limited by the electrical coupling, i.e. good if the coupling ranking were good.

TABLE 5-4

PREFERENTIAL LISTING OF DATA HANDLING SUBSYSTEM COMPONENTS

TYPE	RANKING	COMMENTS
1. Paper Charts, (Analog Recorder)	Good	Simple storage of large amount of data
2. Magnetic Tape (Analog Recorder)	Acceptable	Costlier than chart recording but better form of data for analysis
3. Magnetic Tape (Digital Data)	Good	Good but choice may be made on basis of other DWP EDP requirements such as cargo handling control
4. Disc and Floppy Disc	Good	Same as 3.
5. Paper Tape	Unacceptable	No on line retreival of data for use by Warning Subsystem and Prediction System. Unsuitable for handling the amount of data required.
6. Card	Unacceptable	Same as 5.

TABLE 5-5

RANKINGS OF INDIVIDUAL WARNING DEVICES

DEVICE	ABILITY TO GET AND HOLD ATTENTION	ABILITY TO CUE OR DIRECT ATTENTION	COMMENTS
1. Horn, siren, bell, etc.	Good	Acceptable	Best for getting and holding attention
2. Voice Message	Acceptable	Good	Good when specific immediate attention is required
3. Lights--Steady	Unacceptable	Acceptable	Generally not useful above
4. Lights--Flashing	Acceptable	Acceptable	Useful as a cueing device, but not to get attention
5. Written Message	Unacceptable	Good	Best for directing action and for decision making

TABLE 5-6

RANKINGS OF COMBINATIONS OF WARNING DEVICES

COMBINATION OF DEVICES	ABILITY TO GET AND HOLD ATTENTION	PRECISENESS OF MESSAGE	SIMPLICITY OF COMMUNICATIONS	COMMENTS
1. Horn and Light	Good	Acceptable	Good	Widely used at present
2. Horn and Written Message	Good	Good	Acceptable	
3. Horn, Light and Written Message	Good	Good	Acceptable	Best Overall System
4. Horn, Light and Verbal Message	Good	Acceptable	Acceptable	Possible confusion between aural messages
5. Horn, Light, Verbal and Written Message	Good	Unacceptable	Unacceptable	Multiple devices likely to cause confusion
6. Verbal Message and Light	Good	Acceptable	Acceptable	
7. Verbal and Written Message and Light	Good	Good	Unacceptable	Almost as good as 3.

TABLE 5-7

PREFERENTIAL LISTING OF DATA DISPLAY SUBSYSTEM COMPONENTS

TYPE	RANKING	COMMENTS
1. Strip Chart Recorders	Good (In Control Room And On Ship)	Have been used with most existing MLMSs both ashore and on ship's bridge.
2. Oscilloscope (CRT)	Good (On Ship) Acceptable (In Control Room)	Can display analog data and alpha-numeric messages, but may require additional circuitry. If used in control room, a magnetic tape recorder would be required to store data.
3. CRT Terminals	Good (In Control Room) Unacceptable (On Ship)	Can display all types of data, warnings, messages and graphics. Too large and expensive to carry aboard ship.
4. Meters-Digital	Good (In Control Room And On Ship)	Accurate, inexpensive and, with proper choice of readout devices, can be seen at a large distance.
5. Meter-Analog	Acceptable (In Control Room And On Ship)	Accurate, inexpensive but cannot be read as well or accurately as digital meters.
6. Lighted Bar Charts	Acceptable (In Control Room And On Ship)	Same as 5.
7. Digital Printers	Acceptable (In Control Room) Unacceptable (On Ship)	Is not as cost effective or useful as CRT Terminals and cannot be seen well from large distances.

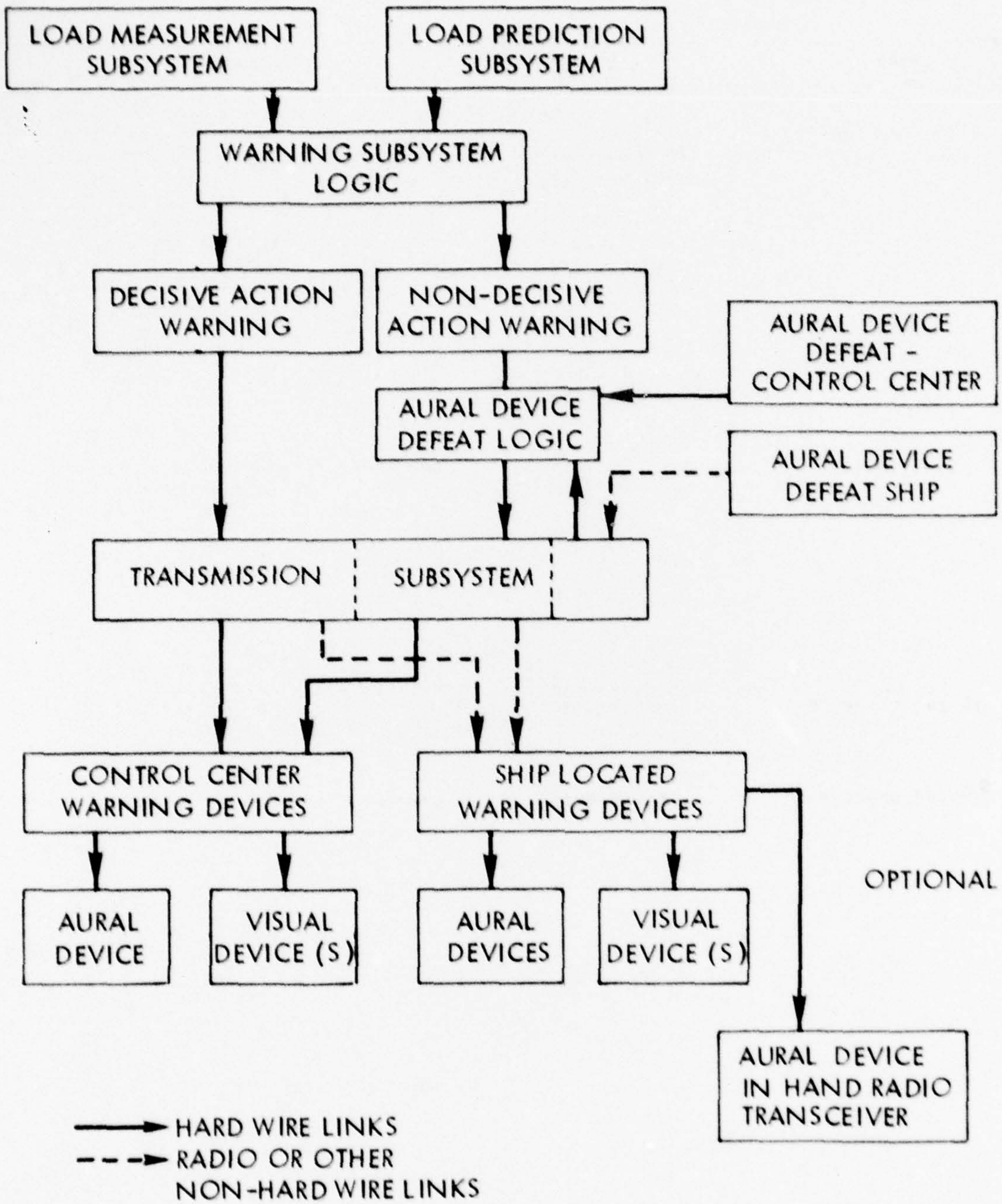


FIGURE 5-1 - RECOMMENDED WARNING SUBSYSTEM

SECTION 6

MOORING LOAD PREDICTION SYSTEMS

6.1 INTRODUCTION

A deepwater port mooring load prediction system (MLPS) will generally be used to predict expected hawser loads at some future time, as discussed in this section. In addition, the MLPS may be used to predict allowable hawser loads based on hawser condition, age, loading history or on current details of loading. This second function is discussed in more detail in Section 8. An evaluation of various MLPSs is given in Section 7.

Methods for predicting mooring loads at a future time will probably be based on a prediction of the expected environment at that time, as well as a means for predicting the mooring load as a function of the environment and ship characteristics. At present, accurate long-term predictions require: accurate predictions or forecasts of wind, wave and current conditions; and model test data for the ship, SPM, and environmental conditions of interest.

In this section both the prediction of hawser loads for known or estimated environment and the prediction of environment are considered. Detailed descriptions of various predictional methods are given in Appendices D, E and F.

A U. S. DWP will probably subscribe to a weather service. This service would provide weather predictions and predicted wind speeds and directions for periods of a few hours to perhaps 48 hours. It is also assumed (LOOP, 1976) and (Seadock, 1976) that the DWP could measure, process and store wind and current speed and direction and wave height and period data. Processing would probably consist of determination of mean wind and current speed and direction and significant wave height and period. Averaged

data for fixed time intervals (say 15 or 30 minutes) could be stored for the duration of the ship mooring.

The weather service might also provi.e predicted wave and current conditions. It is likely, however, that the DWP might have to predict future wave heights and periods based on existing wind and wave conditions and predicted wind conditions. These predictions will be complicated by the shallow water depths likely to exist at the DWP. A further complication for a U. S. Gulf DWP is the difficulty in predicting wave heights for the local but relatively severe squalls which occur in the Gulf of Mexico.

6.2 METHODS FOR PREDICTING FUTURE HAWSER LOADS

The nature of a hawser load prediction method will depend on the required or desired time period of the prediction or forecast. Short-term predictions, which are valid for perhaps one-half hour to one hour, can be based on relatively simple extrapolation techniques. Long-term predictions, which are valid for several hours, or perhaps for a whole cargo transfer operation, require fairly sophisticated methods for describing the environment and for predicting loads resulting from that environment.

A number of predictional methods are available. These range from the simplest, a human extrapolation based on present and recent past history of loads and environment, to complex theoretical methods or highly developed empirical methods suitable for predicting hawser loads for an arbitrary cargo transfer operation. The first type is the only one currently in use today, and can be used effectively at ports with load monitoring systems. Empirical methods developed by SPM designers may be in use at a few ports to estimate hawser loads, but such methods are proprietary and are likely to be generally unavailable.

Table 6-1 presents a characterization of five prediction

techniques, listed in order of increasing period of applicability and complexity. These methods and their suitability for deepwater port use are discussed in Sections 6.3 to 6.6. The various methos are rated in Section 7.

6.3 SHORT-TERM EXTRAPOLATION METHODS

These methods (Methods 1 and 2 of Table 6-1) provide a means for predicting, based on current conditions, the maximum hawser load expected over a short following period, say 30 minutes. Because wind speed and wave heights can change rapidly in areas such as the Gulf of Mexico, it is desirable to include at least the effect of any predicted change in wind speed (see Appendix F).

6.3.1 Human Extrapolation

This method, which is used at existing deepwater ports, is based on human judgement and synthesis of the following information:

1. Current or most recent peak hawser load.
2. Rate of change of peak hawser loads.
3. Rate of change of wind velocity.
4. Yawing motion of the ship.
5. Loading condition (draft and trim) of the ship.

A load monitoring system and an anemometer are required for Items 1 and 3. Item 2, requires a strip-chart recorder or other time history display of loads. Yawing motions are generally estimated by personnel on the ship. This method will probably be satisfactory only if a time history display of loads and wind are available at all times and if skilled and experienced personnel are making the extrapolation.

In Appendix D four possible schemes for making short-term predictions of peak hawser loads are described. These are based

on stored and/or up-dated empirical relationships between the maximum or peak hawser load and the environmental conditions. These methods can be summarized as follows:

1. Prediction of peak load from predicted environment (wind speed, wave height and current speed) using a fixed empirical relationship.
2. Prediction of peak load from prediction of environment using empirical equations which are applicable only to the tanker size of interest.
3. Prediction of peak load as in approach 2, except that the empirical equation would be modified or updated using data obtained during the earlier part of the mooring sequence.
4. Prediction of mean load as in approach 3, and use of an empirical relationship between mean and peak load applicable to the tanker size of interest.

For each of these schemes various methods, as described in Appendix F, can be used to estimate the environment.

6.3.2 Automated Extrapolation

In this approach (Method 2 of Table 6-1), the extrapolation is done automatically using a computer and using a prescribed technique such as described in Section 6.3.1 and using most or all of the following data:

1. Current wind speed, wave height and hawser load.
2. Variation of wind speed, wave height and hawser load over a preceding period of, say one hour.
3. Predicted change in wind speed over a following period of, say one-half hour.
4. Empirical trends in hawser load with wave height and wind speed.

Various extrapolation techniques based on these data can be de-

veloped. A number of techniques have been considered and, based on an analysis of the NSMB LOOP/Seadock data (Remory and Wickers, 1975), several techniques are outlined below and described in more detail in Appendix D. Methods for predicting changes in environment are described in Section 6.7 and Appendix F.

6.4 MEDIUM-TERM EXTRAPOLATION METHODS

These methods (Method 3 of Table 6-1) would probably be an extension of a short-term method, such as described in Section 6.3.2 and Appendix D, or an empirical method such as the Exxon energy method (Maddox, 1972).

When extrapolation methods are used, the primary difference from short-term methods would be in the use of better and longer term predictions of wave height and period and current speed and direction from predicted winds.

Peak hawser load would be predicted for regular time intervals, say one-half hour, using appropriate predicted wind and waves. The magnitude of and estimated time of occurrence of the largest peak hawser load would be determined. The primary problem would be the accurate prediction of environmental conditions for longer periods and prediction of loads for rather arbitrary combinations of wind speed and wave height.

An energy method (Maddox, 1972) and (Flory, et al., 1977) which has been used to predict SPM hawser loads has been developed by Exxon. This method is illustrated by equating the significant energy of two different SPM's, given identical ships and environments. The significant energy is defined as the potential energy stored in the buoy, buoy mooring and hawser at a load equal to the significant load. The significant load is the average of the one-third highest loads. The method provides a method for predicting the significant load occurring in a given environment and ship

for an arbitrary SPM. Attempts during this study to establish similar relations between hawser load and the stored energy for arbitrary environments and ships, using NSMB LOOP/Seadock model test data (Remory and Wichers, 1975), were inconclusive.

6.5 LONG-TERM EMPIRICAL PREDICTION METHODS

This method (Method 4 of Table 6-1) could be used for a given buoy and hawser to make long-term, or short-term, predictions of maximum and/or mean hawser load based on ship characteristics and predicted environmental conditions. It would make use of and require a large data base and a computer or microprocessor to store, update and access this data base. This data base could be acquired from several years operation of a U. S. deepwater port or from extensive and costly systematic model testing.

The required data base must be segregated according to important ship and environmental factors. The factors of primary importance in describing the hydrodynamics and aerodynamics of typical tankers are displacement, draft and freeboard or displacement, design draft and state of loading. Ship factors which are generally of lesser importance are bow shape (T2, bulbous or cylindrical), number and location of deck houses and number of screws. Environmental factors which are of primary importance include wave height, period and direction, wind speed and direction, and current speed and direction.

For a given buoy and hawser, hawser load must be stored for a number of values of each important ship and environmental parameter. The minimum number of values is that required for interpolation; ideally enough values should be used to eliminate the need for interpolation. Tables 6-2 and 6-3 show representative numbers of value for each parameter and total data file require-

ments for a comprehensive non-interpolution scheme and for a basic scheme using interpolution. It is possible to use these schemes for portions of the total matrix (say for limited ranges of ship displacement, etc.). Data for only 10 percent of these cases might be adequate for more than 50 percent of all moorings.

The use of the comprehensive scheme described in Table 6-2 is considered impractical due to the large period of time required to acquire the necessary data even for a small range of ship cases. If only 10 percent of the total cases in the matrix were of interest and if a load were determined every half hour, more than 40,000 hours of DWP operation (4.6 years operation of four buoys at 70 percent utilization) to acquire the required 230,000 data points, and the file would still be far from complete due to multiple repetition of many points. It should be feasible, however, to acquire the most useful portions of the 5,800 data points required in the interpolation scheme of Table 6-3 in less than a year. The system would probably prove useful after several months of full DWP operations. Provisions could be made for upgrading the rather minimal scheme of Table 6-3 by providing a larger initial storage capacity.

The primary advantage of this method is the possibility of predicting, with potentially good accurace, the hawser loading history for as long a period as good environmental predictions are available. This method should be more accurate than other available long-term predictional methods. The primary disadvantages are the time and computer storage required to generate and store the data file and the need for operating personnel to determine and key into the system ship characteristics and updated weather forecasts. Ship characteristics could be obtained either from the ship's master or from documents such as the ABS Record (ABS, 1978). Ships having the same gross characteristics may

have quite different loads, so care must be exercised.

This method can be used to make short-term predictions, but may be less accurate for this purpose than the short-term extrapolations which use current measured loads as a base.

6.6 LONG-TERM THEORETICAL-EMPIRICAL METHODS

Theoretical or theoretical-empirical methods, as described recently (Owen and Linfoot, 1976) and in Appendix E of this report, provide the only probable alternative to model tests for prediction of ship-buoy behavior and hawser loads for an arbitrary ship-hawser-buoy configuration in an arbitrary environment. These methods have several drawbacks, including limited availability of required ship shallow water hydrodynamic force data, the need for relatively large computer capability and, most significantly, potentially poor accuracy.

The inability of available theoretical methods to accurately predict hawser loads was a primary reason for the emphasis in the Exxon Phase I Report (Flory, et al., 1977) on model tests. Discussions with Exxon and review of existing work led to a conclusion that some potentially important factors might have been neglected in previous work and that the suitability of theoretical-empirical methods incorporating these factors should be re-examined.

A computer simulation of the behavior, in the time-domain, of a ship-SPM system was developed from previous work at HYDRONAUTICS (Barr, et al., 1976) and (Altmann, 1971). In this simulation the SPM is assumed to consist of a CALM or SALM buoy, a non-rigid buoy mooring, and a hawser connecting the ship and buoy. This simulation, which is described in detail in Appendix E, is based on the following assumptions:

1. The ship is represented by non-linear coupled surge, sway and yaw equations of motion and by hydrodynamic coefficients determined from planar motion mechanism (PMM) tests in shallow water.
2. Wind and wave forces acting on the ship are based on available data for tankers and full form ships.
3. The buoy is represented by coupled surge and sway equations of motion. Hydrodynamic coefficients and wind and wave forces acting on the buoy are based on available data for circular buoy forms.
4. The hawser and buoy mooring are represented by non-linear, force-deflection curves.
5. The coupled five-degrees-of-freedom equations of motion for the ship-SPM are solved by a time-step numerical integration.

The suitability and potential accuracy of this method depends on the availability of suitable hull hydrodynamic coefficients, wind and wave force data for the ship and buoy and mooring and hawser force-displacement curves. The latter can usually be accurately determined.

An initial validation of the method was made by simulating the motions of a ship-CALM system which had been tested (Owen and Linfoot, 1976) and comparing the results with the model test data. It was necessary to assume details of ship geometry and mooring and hawser characteristics. The latter were based on representative data (Remery and Wichers, 1975). Simulations were made for a significant wave height of 13.1 feet while model tests were for 13.1 foot high regular waves. The simulated motions are shown in Figure 6-1. Motions appeared to be dominated by mean, rather than instantaneous or peak wave drift forces.

Despite the assumptions, there is qualitative agreement of results as shown in Table 4.

Simulations were made, for the purpose of validation, for five SALM buoy cases from the LOOP/Seadock model tests (Remery and Wichers, 1975). Four cases were for full load displacement and one case (run 2102) was for ballast. The simulated and measured results are presented in Table 6-4. Agreement is better for ship motions than for hawser tensions, and is better for the ballast than for the full load condition. Agreement for mean hawser tensions is not bad (rms error of 25 percent for the five cases) but agreement for maximum hawser tensions is unacceptable, predicted values being 45 percent or less of measured values.

A number of additional runs were carried out, as described in Appendix E, to try to understand the reason for the under-prediction of hawser loads. While these provided some insights they did not provide any means for significantly improving predicted results. It is therefore concluded, as has been concluded by Exxon, that current theoretical-empirical methods of this type are not adequate for predicting hawser loads.

6.7 ENVIRONMENTAL MEASUREMENTS

It will be necessary to measure wind, waves and current as part of any MLPS. It will also be important, if not essential, to make these measurements when an MLPS is not used, as these data will be an important part of any decision-making process. Techniques for measuring wind, waves and current are well developed and are not considered in detail here. A few aspects of measurement techniques require discussion, however.

It is assumed that a U. S. deepwater port will have a large offshore pumping platform complex (PPC) in the immediate vicinity of the SPM and that all environmental measurements will be made

at the PPC. At any DWP location where waves or current can come from a wide range of directions, the location of the wave and current sensors or probes must be carefully selected to ensure that the measurement of waves and current are not effected by the platform structure. In some cases this may require mounting these sensors from a boom or from a tethered buoy. It is required that a clear location for an anemometer at an appropriate height (say 30 to 60 feet) above the water be provided.

If a PPC is not used at the DWP or is at a water depth which is significantly different than the water depth at the moorings, it will be necessary to locate wind, wave and current sensors on a separate data buoy near the moorings. An additional radio transmission link with at least five data channels will be required in this case.

Multiple wave probes have previously been required to measure wave direction. Recently developed research techniques (Oakley, 1977) make possible the determination of wave direction with only three probes plus sophisticated computer processing of data. At the present time such techniques are not considered appropriate for a DWP. A more recent technique (Brainard, 1978) requires only the use of one wave buoy and may be well suited for DWP use. Alternately, a manual input of wave direction as observed on the platform or the ship could be used. The platform is a better choice since its orientation is fixed.

Equipment for measuring wind velocity and direction are readily available. Methods for measuring current velocity and direction are not as well developed and care must be taken to ensure that the measured values are not influenced by the PPC. Mavor, Poranski and Walden (Mavor, et al., 1976) described a method for measuring current using a bottom fixed spar buoy and

radio telemetry that can eliminate any influence of the PPC.

6.8 PREDICTION OF WAVE HEIGHTS

Any MLPS will require some means for predicting future wind, waves and current. It is assumed that predictions of wind speed and direction, as a minimum, will be obtained from a weather forecasting source. If predictions of wave height and period and current speed and direction are not obtained from such a service, it will be necessary for the DWP to make these predictions. For short-and medium-term prediction schemes, it may be sufficient to predict only wave height and period, as currents generally change slowly.

Available methods for predicting wave height and period are discussed in Appendix F. Existing predictional methods are, typically, graphical and must be adapted to an automated computer prediction method. From available results, it is not clear how accurate such predictional methods are for shallow water (water depths less than a few hundred feet), which is the probable situation for most U. S. DWP's (LOOP, 1976) and (Seadock, 1976). Short-or medium-term predictions based on changes from measured existing conditions will probably be adequate for DWP needs, however.

TABLE 6-1

CHARACTERIZATION OF LOAD PREDICTION METHODS

Method - Period of Applicability	Primary Technique	Required Inputs	Important Steps In Process
1. Human extrapolation (up to one-half hour)	Purely Empirical	1. Consecutive Values of Peak Load 2. Change in Wind Velocity and/or wave height	1. "Seat-of-pants" extrapolation reflecting change in wind or waves
2. Short-Term Extrapolation (one-half to one hour)	Primarily Empirical	1. Peak and Mean Loads and Mean Wind Speed for four previous Δt's 2. Wind Speed Prediction (optional)	1. Extrapolate wind speed (if necessary) 2. Extrapolate mean force 3. Extrapolate maximum force using 1 and 2 above
3. Medium-Term Extrapolation (one to six or more hours)	Primarily Empirical	1. Peak and Mean Loads and Mean Wind Speed and Wave Height 2. Predicted Wind Speeds for Desired time increment	1. Predict wave height for predicted wind speed 2. Predict mean and maximum forces for each 1/2 hr. 3. Determine peak loads
4. Long-Term Extrapolation (up to 48 hours)	Purely Empirical (using large operational data base)	1. Basic Ship Characteristics 2. Predicted Wind Speeds for Desired time increment 3. Current Mean Wind Speed and Wave Height	1. Predict wave heights for predicted wind speeds 2. Predict peak forces for each hour 3. Determine peak load
5. Long-Term Extrapolation (up to 48 hours)	Primarily Theoretical	Same as 4.	Same as 4.

TABLE 6-2

DEFINITION OF DATA BASE MATRIX FOR COMPREHENSIVE PREDICTION SCHEME REQUIRING LITTLE OR NO INTERPOLATION

Prediction Parameter	Number of Values Required
Ship Displacement	6
Ship Design Draft	3
Ship Loading	5
Bow Shape	3
Deck House Configuration	2
Number of Screws	2
Wind Speed	4
Wind Direction (Reference Direction)	1
Wave Height	4
Wave Period	3
Wave Direction	3
Current Speed	3
Current Direction	5
Total Data File Words	2,332,800

TABLE 6-3

DEFINITION OF TYPICAL DATA BASE MATRIX FOR MINIMAL PREDICTION SCHEME USING INTERPOLATION

Prediction Parameter	Number of Values Required
Ship Displacement	4
Ship Design Draft	3
Ship Loading	3
Wind Speed	3
Wind Direction (Reference Direction)	1
Wave Height	3
Wave Period	3
Wave Direction (Reference Direction)	1
Current Speed	2
Current Direction	3
Total Data File Words	5,832

TABLE 6-4

COMPARISON OF COMPUTER SIMULATION AND MODEL TESTS
(Owen and Linfoot, 1975)

	Simulation	Experiments
Period of Oscillation Secs.	800	1100
Yaw Amplitude Radians	.4	.4
Sway Amplitude Ft.	80	120
Surge Amplitude Ft.	168	104
Mean XCG Ft.	-531	-577
Phase lag of Sway behind Surge Sec.	300	400

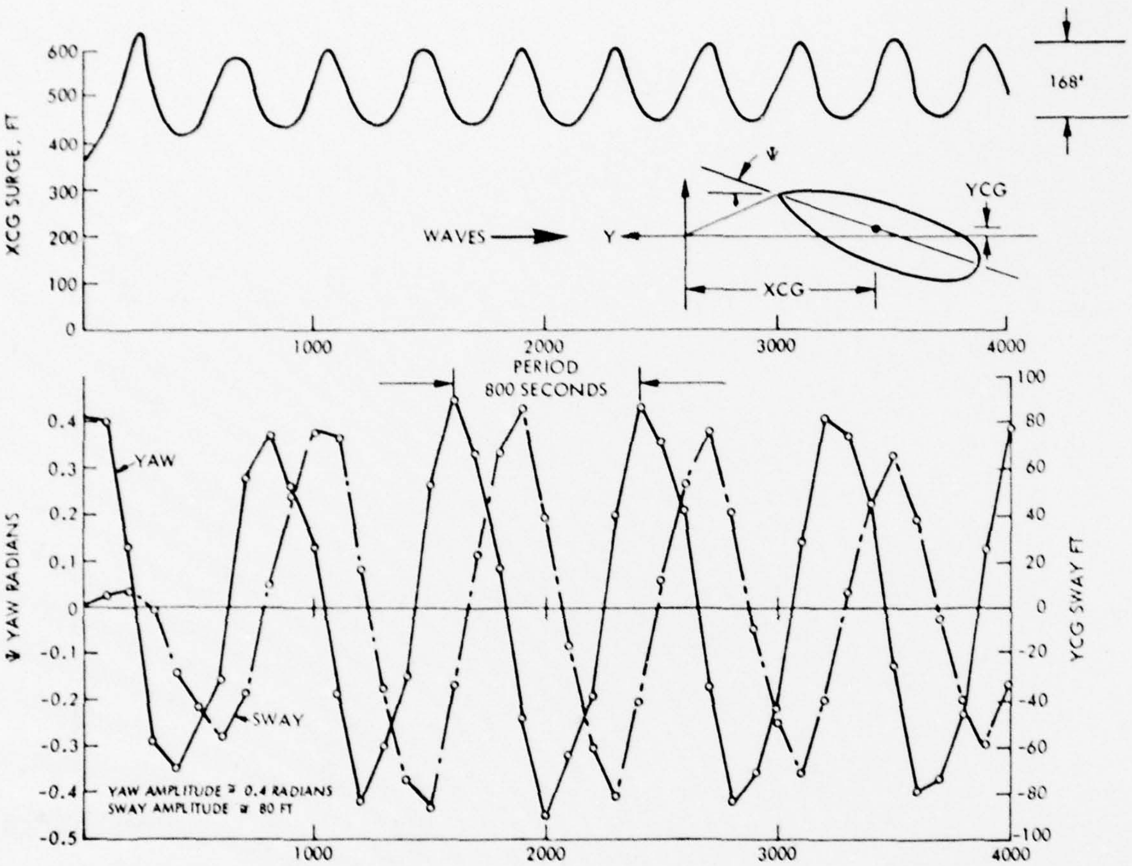


FIGURE 6-1 - COMPUTER SIMULATION FOR CASE OF OWEN AND LINFOOT

SECTION 7

RANKING OF MOORING LOAD PREDICTION SYSTEMS

In order to determine what, if any, mooring load prediction system (MLPS) is required or recommended for use at a U. S. DWP, it is necessary to critically evaluate and rank the various types of MLPS considered in Section 6. The advantages and disadvantages of the five basic types described in Table 6-1 are discussed below.

7.1 SHORT-TERM HUMAN EXTRAPOLATOR

This method depends entirely on the experience and judgement of the port personnel or ship's master. It is used at existing DWP to make important operational decisions and is usually, but not always, an adequate predictional tool.

7.2 SHORT-AND MEDIUM-TERM EMPIRICAL METHODS

These methods are generally identical except for the required period of prediction of wind, waves and current. The environmental factors can generally be predicted much more accurately for one hour than for six hours. The predictional scheme can be quite accurate, particularly for short periods, when empirical relations are updated or corrected using measured results for the current mooring. The primary source of inaccuracies in such cases will probably be in prediction of wave height. For the load prediction methods considered in Appendix D, computer hardware and software requirements are modest.

7.3 LONG-TERM EMPIRICAL METHOD

These methods are similar to the shorter-term empirical methods, but generally a much larger data base will be required and a lower accuracy will be obtained since updating of current mooring results is not effective. Long-term wave and current predictions will also be less accurate than short-term predictions.

The large data base will require significant computer storage capacity.

7.4 LONG-TERM THEORETICAL METHOD

Further development is required to achieve acceptable accuracy. The behavior of a SPM may, in fact, be too complex to be accurately predicted by existing time-domain methods. Relatively large computer memory and computational speed are required. The time-domain calculations must be carried out at 10 to 20 times real time to maintain up-to-date, long-term predictions.

7.5 CRITICAL RANKING OF VARIOUS METHODS

The methods summarized in Sections 7.1 to 7.4 are ranked according to general usefulness, expected accuracy and computer hardware and software requirements in Table 7-1.

General usefulness is an assessment of how valuable the type of results provided are for DWP decision making. A method which can be employed to make accurate short-, medium- and long-term load predictions is clearly the most useful. Accurate predictions for short- and medium-term periods (up to six hours) will generally be more useful than will accurate prediction for long-term periods.

The computer requirements reflect the sophistication and extent of hardware and software required to process and store mooring load data, environmental data and predictional methods. In general, the biggest differences are in storage requirements.

The assessment of expected accuracy is based on the results described in Appendices D, E and F. The "good" rating for the short-term methods reflect the promising results described in Appendix D. The "unacceptable" rating of the long-term theo-

retical method is based on the poor results described in Appendix E; it seems possible that acceptable accuracy might be obtained with further development of such methods.

7.6 RECOMMENDATIONS

It is concluded that any DWP should be required to provide basic data needed by DWP personnel for making short-term empirical mooring load predictions. These data, which would consist at a minimum of short-term hawser load history, measured current and wind velocity, and wave height and period should be available to operating personnel at all times. It is strongly recommended that an automated MLPS, based on short-term empirical prediction methods, as described in Appendix D, be used in conjunction with a MLMS. This will provide a more rational basis for decision making and should result in greater DWP utilization. If such an automated system is used, the system should provide the capability of displaying all basic input data.

It is further concluded that a DWP should be required to measure and process wave height and period, wind speed and direction, and current speed and direction, as described in Section 6.8. These data should be displayed or be available for display at the control center at all times. They will also be processed for use in any MLPS. With the advent of methods for measuring wave height and direction using a single buoy (Brainard, 1978) it may be desirable to require measurement of wave direction as well as wave height and period.

TABLE 7-1

RANKING OF MOORING LOAD PREDICTION SYSTEMS

	Prediction System	General Usefulness	Expected Accuracy	Computer Requirements	Comments
1	Short Term Human Extrapolator	Acceptable	Variable	None	Accuracy depends on ability of personnel and available data.
2	Short-Term Empirical	Acceptable to Good	Good	Good	Recommended but not required for initial U.S. DWP's.
3	Medium-Term Empirical	Good	Acceptable to Good	Good	Identical to 2 for short-term. Extra duration of prediction could be useful.
4	Long-Term Empirical	Good	Acceptable	Acceptable (see comment)	Will take a long time to acquire needed data. Computer storage could be excessive for some DWP's.
5	Long-Term Theoretical	Acceptable	Unacceptable (at present)	Acceptable	Not feasible at present. Could be a useful tool if developed.

SECTION 8

DETERMINATION OF ALLOWABLE MOORING LOADS AND WARNING LEVELS

The determination of allowable mooring loads is discussed in some detail in the Exxon Phase I report (Flory, et al., 1977). In this section the impact of available information, including that presented in the Exxon Phase I report, on the design and operation of mooring load monitoring and prediction systems is considered.

Hawser elastic properties and breaking strength are a function of rope condition, age, loading history and loading rate. Allowable hawser load and mooring load warning levels should take these factors into account.

Sufficient data are not presently available to determine the magnitude of losses in rope strength with rope age, loading history or rate of loading. Sufficient data are available, however, to indicate the existence of losses in strength and the need to reflect these losses in determining allowable loads. Ideally, an MLMS orMLPS should be able to automatically change warning levels to reflect changes in allowable hawser load. This is not presently feasible but should be a goal for future systems.

Allowable mooring loads and required warning levels may be determined by ship mooring fittings, as discussed in the Exxon Phase I report. The difficulty in determining allowable mooring fitting strength is discussed in Section 8.4.

Since it is not currently possible to provide specific methods for predicting changes in allowable mooring loads, no evaluation of the type given in Sections 5 and 7 is possible.

8.1 REDUCTION OF STRENGTH DUE TO DAMAGE

Physical damage to the hawser is a primary cause of reduction in hawser strength. Physical damage can generally be determined by careful inspection of the entire hawser. Such an inspection would probably be carried out by bringing the hawser aboard a work boat or launch. Such inspections should be required shortly before each mooring. Decisions on hawser replacement will be made by cognizant personnel on the basis of the inspection. Chemical damage which can occasionally be a problem may be impossible to detect by inspection.

It may be feasible to develop, with the aid of rope manufacturers, criteria for hawser replacement based on the depth and circumferential extent of well defined physical damage. It is not presently feasible, however, to accurately determine the loss in hawser strength from observations of damage. It is therefore desirable for cases of non-superficial hawser damage to remove and test the hawser to determine if it can be safely placed back in service. Such testing will require a special test facility such as that being developed at Anglesea.

There are no well recongized, non-destructive methods for predicting a reduction in hawser strength, but the method used by Shell at Anglesea may provide a useful tool. In this method each hawser is loaded, when new and during its operating life, to two levels, say one and 50 tons of tensile load, and the length for each load is measured. Qualitative assessments of reduction in breaking strength can be made from changes in length, particularly with a damaged hawser. With sufficient data, it may be possible to make quantative predictions of reduction in breaking strength.

The primary drawbacks of this method are the difficulty in

applying large loads to the hawser and the required time and cost to transport the hawser to and from the test site, which will probably be ashore. An in-situ test method, if available, would be preferable and would be more likely to be used in cases of marginal hawser damage.

8.2 REDUCTION OF STRENGTH DUE TO CYCLIC LOADING

Repeated cyclic loading of the hawser will result in a decrease in hawser strength with age, as discussed in the Exxon Phase I report. This decreased strength can affect allowable hawser load in several ways:

1. Repeated cyclic loadings at a level well below static strength can result in failure during cyclic loading at this load level.
2. After repeated cyclic loadings which do not produce failure, static breaking strength will be reduced.
3. A rope, after repeated cyclic loadings, will have lower breaking energy than a new rope and the breaking strength for dynamic or shock loadings must be selected accordingly.

The first two areas are discussed below, the third is discussed in Section 8.3.

The behavior of synthetic ropes under cyclic loading is not yet well understood. The behavior is more complex than that for steel wire rope, where failure occurs when the sum of all cyclic loads exceeds a given value. Some guidance can be obtained, however, from available cyclic loading test data.

Figure 8-1 shows a collection of cyclic loading results for nylon, polyester and polypropylene ropes from various sources (Flory, et al., 1977). Data are shown for cases where failure occurred (solid symbols) and where no failure occurred (open

symbols). These data are for tests of different rope materials, sizes and types, tests in air and water, and tests at different frequencies. Despite these differences it seems possible to draw several useful conclusions from available data, including:

1. For cyclic loading breaking strengh decreases, at least for nylon and particularly for polypropylene, with increasing number of loading cycles.
2. Polyester appears to suffer a much smaller decrease in strength for cyclic loading than do nylon and polypropylene. Nylon generally appears to be superior to polypropylene.
3. There is no clear evidence that an asymptote exists for breaking strength, as postulated in the Exxon Phase I report, although no failures have been recorded for cyclic loads less than 45 percent of static breaking strength.

It should be noted that all cyclic loading tests have been carried out with relatively small ropes and at frequencies (one to two cycles per minute or cpm) which are lower than typical wave induced cyclic loading frequencies (five to 15 cpm). Data from systematic tests of large ropes at higher frequencies are needed to establish realistic factors of safety and acceptable loads for hawsers. It is understood that cyclic tests of large new and used hawsers are currently being carried out by Consolidated Equipment Company. The results of these tests are likely, however, to be proprietary.

Data, such as those presented in the Exxon Phase I report, indicate that reductions of static breaking strength after significant cyclic loading, are probably no more than ten percent for polyester, 6.6 nylon and polypropylene ropes. This reduction is not significant if the allowable working load or the factor of

safety is as proposed in Section 8.5 or the Exxon Phase I report.

Wilson (Wilson, 1973) discusses in some detail changes in rope elastic properties with cyclic loading and age. These data indicate that as a rope ages, the breaking strength may not decrease significantly. Available data (Wilson, 1973) indicate decreases of up to 50 percent in breaking energy for twisted nylon ropes. The actual situation is probably rather more complex, as discussed below (McKenna, 1978).

The total energy absorption capability of a fiber and of a rope is a function of two factors, one related to material bulk modulus, which does not change with age or load history, and one related to mechanical working of fibers which changes with age, primarily during initial loading cycles. After a relatively modest number (as few as 50) of load cycles and with no load exceeding 30 percent of breaking strength, mechanical working and rope properties will stabilize. The energy absorption capability of this stabilized rope will thereafter remain relatively constant unless the rope is loaded to more than 30 percent of breaking strength. It may be more appropriate to use the properties of this stabilized rope, rather than those of new rope, to determine allowable loads. It should be noted, however, that repeated loading over long periods will cause gradual reduction in energy absorption capability. These factors must be taken into account in any consideration of dynamic loading.

8.3 STRENGTH REDUCTION DUE TO HIGH LOADING RATES

Maximum hawser loads usually occur as a result of large motions of the moored ship. These motions can produce sudden hawser snatch or impact loads. Existing load monitoring systems are probably not able to sense the resulting high loading rates and instantaneous maximum loads. Samson Ocean Systems has indicated that the hawser strength can be significantly

reduced by high loading rates. At North Sea SPMs, loading rates up to five percent of breaking strength per second have been recorded (McKenna, 1978). These high loading rates have produced noticeable reductions in hawser life (McKenna, 1978).

Experimental results for synthetic ropes up to three inch circumference (Borwick and Elliot, 1972 and Dickie, 1975) indicate significant reductions in breaking strength can occur at high loading rates. Figures 8-2 and 8-3 (from Borwick and Elliot, 1972) show variations of breaking load and total energy absorbed before breaking with initial loading rate. The energy absorption is perhaps of greatest interest, since snatch loadings are usually associated with large energy transfer from ship to SPM. Polypropylene has the greatest percentage loss in breaking load while nylon has the greatest percentage loss in breaking energy, about 50 percent for a 60 foot per second loading rate.

Table 8-1 and Figure 8-4 show impact loading results determined from falling weight tests of small braided ropes, (Dickie, 1975). Table 8-1 indicates dynamic breaking loads of 33 to 58 percent of static breaking load. The impact velocities for these tests, as shown in Figure 8-4, are about 19 to 23 feet per second. For these impact velocities, the NEL data of Figure 8-2 show breaking loads of more than 80 percent of static breaking load. These differences are probably due to the shorter rope lengths and nonaxial loading and perhaps to the more rapid rate of change of velocity in the Canadian tests. The Canadian data show significant reductions in breaking load, for a given impact velocity, with decreasing rope length, due no doubt to decreased energy absorption capability. Sampson feels, that under dynamic loading, hawser breaking strength can be significantly reduced by non-uniform fiber loading.

At present, there are not sufficient data to define a useful quantitative relationship between breaking strength or allowable load and impact velocity (loading rate) and energy. This relationship clearly needs to be determined. Such relationships could only be effectively used in a MLMS or MLPS if the MLMS frequency response was sufficiently high to determine maximum rates of change of load during impact type loadings, such as occur when the ship, in yawing about the buoy, suddenly pulls the hawser taut.

It should be noted that all test results described are for new ropes. Stabilized or used ropes have, as described in Section 8.2, lower breaking energy than new ropes. Impact tests of stabilized or used ropes are clearly needed.

8.4 ALLOWABLE SHIP MOORING FITTING LOADS

The influence of ship mooring fitting strength on allowable mooring load is discussed in some detail in the Exxon Phase I report. Clearly the hawser load should not exceed a safe fitting load, which is defined as one-half the ultimate capacity of the fitting. The hawser and mooring fittings must also be compatible, to ensure that the full strength of each can be realized.

For well designed, fabricated and installed fittings, which are in good condition (not badly rusted, pitted, etc.), safe or allowable loads are a function of fitting size. It is not possible, however, to determine by visual inspection if a mooring fitting is well designed, fabricated and installed. Unless shipyard drawings of the fittings are available, which will generally not be the case, safe fitting load can be determined only by methods such as x-ray or ultrasonic inspection.

It is probably not feasible to bring the necessary equipment aboard ship for inspections, unless a ship is certain to visit

the DWP on a regular basis. This generally cannot be assured for a common carrier or open port. It will therefore probably be possible only to determine the type of mooring fittings, their general appearance and their condition, and to determine from these qualitative factors if the allowable mooring load should be less than the allowable hawser load.

8.5 SPECIFICATION OF ALLOWABLE LOADS OR FACTORS OF SAFETY

The factors of safety recommended in Section 5.7.6 of the Exxon Phase I report presently appear reasonable when the hawser governs allowable loads. The two factors of safety criteria given there are:

1. Based on measured peak load
   2.0 for single hawsers
   3.0 for double hawsers

2. Based on significant value of measured cyclic load
   4.0 for all hawsers

Larger factors of safety are clearly indicated with predicted loads. Despite the fact that these are more conservative than other existing standards, such as ABS Rules (ABS, 1975), there exists a need for much better understanding of the dynamic strength of rope and hawsers. Prudence might dictate the use of somewhat larger factors of safety until better data on the properties of large hawsers are available.

At the CONOCO terminal (Linehan, et al., 1975), the MLMS alarm is set at ten percent of estimated hawser static strength, while the largest peak load reported was 17.6 percent of static strength. Based on Samson data for the 21 inch nylon line used and on port operational data (Linehan, et al., 1975), the allowable working load for the hawser should be about 190 tons or 19

percent of static breaking strength. The conservative alarm setting may be a reflection of the early problems experienced at the terminal or concerns of Samson about hawser dynamic strength.

8.6 SPECIFICATION OF WARNING LEVELS

As noted in Section 4.6, it is proposed that the load warning system incorporate two distinct warning levels and signals. The first would indicate the probable occurrence of an excessive load in the near future and the need for extreme vigilance coupled with the use of any available actions, such as rudder steering, to reduce loads. The second would indicate the occurrence of an excessive load and the need for immediate termination of cargo transfer operations. It is proposed that these warning levels be set as follows:

First Level: Measured load reaches 60 to 70 percent of allowable load, as described in Section 8.4 or predicted load during the next 30 minutes reaches 80 percent of allowable load.

Second Level: Measured load reaches 80 to 90 percent of allowable load, as described in Section 8.4 or predicted load during the next 30 minutes reaches 100 percent of allowable load.

If only one warning level is used, it should be set at the first level.

8.7 INCORPORATION OF ALLOWABLE LOADS PREDICTIONS IN LOAD MEASUREMENT AND PREDICTION SYSTEMS

After suitable criteria and methods have been developed for determining or predicting allowable loads as a function of one or more definable parameters (cycles of hawser load, histogram of cyclic loads, rate of extension, etc.), it is desirable to incorporate these methods into the MLMS and MLPS. If no pre-

diction system is used, they would be incorporated into the MLMS. When an MLPS is used, it will probably be most efficient to incorporate these methods into this prediction system, which will require computer hardware and software.

Since necessary criteria and methods for predicting allowable loads do not currently exist, it is not possible to discuss implementation in any detail. It is possible, however, to indicate the types of measurement and stored data which might, based on results discussed in this section, be required. Table 8-2 provides a listing of possible measurements and data storage requirements. In all cases, the hardware and software requirments are minimal.

In any MLMS or MLPS which incorporates one or more means for redefining allowable mooring loads, it is essential that a means be provided to alert port personnel to the current estimation of allowable load. This could be done using a digital display or a CRT data display. Without such information, a warning alarm might be interpreted as a system malfunction.

TABLE 8-1

MEASURED ROPE BREAKING STRENGTH
UNDER IMPACT LOADING - (DICKIE, 1975)

Rope Size and Type	Breaking Strength - Pounds Rated	Breaking Strength - Pounds Failure	Percent Reduction From Rated
1/2" Braided Polypropylene	4,400	1,690	62
5/8" Braided Polypropylene	7,350	3,555	52
1/2" Braided Polyester	7,500	4,313	42
5/8" Braided Polyester	13,000	4,321	67
1/2" Braided Nylon	8,300	3.626	56

TABLE 8-2

POSSIBLE MEASUREMENTS AND DATA STORAGE
REQUIREMENTS FOR ALLOWABLE LOAD PREDICTIONS

Factors Affecting Allowable Load	Parameter to be Measured*	Data Storage Requirement	Computer Processing Requirements
1. Cumulative Cyclic Loading	Mean and Peak Load of Each Cycle	Histogram of Cyclic Loads	For each load cycle the loads are classified by load range and the number of cycles for this load range is incremented.
2. High Loading Rates	Rate of Change of Loading	None	The rate of application of load would be determined from rate of change of load.
3. Reduced Breaking Energy	Elongation Under Fixed Static Loads	Calculated Allowable Load Haswer Properties	The allowable breaking energy would be calculated from measured deflection under load and stored new hawser elastic properties.
4. Inadequate Ship Fitting Strength	Observation Data Keyed In	Input Allowable Load	The estimated allowable ship fitting load would be stored.

*Based on Current Understanding

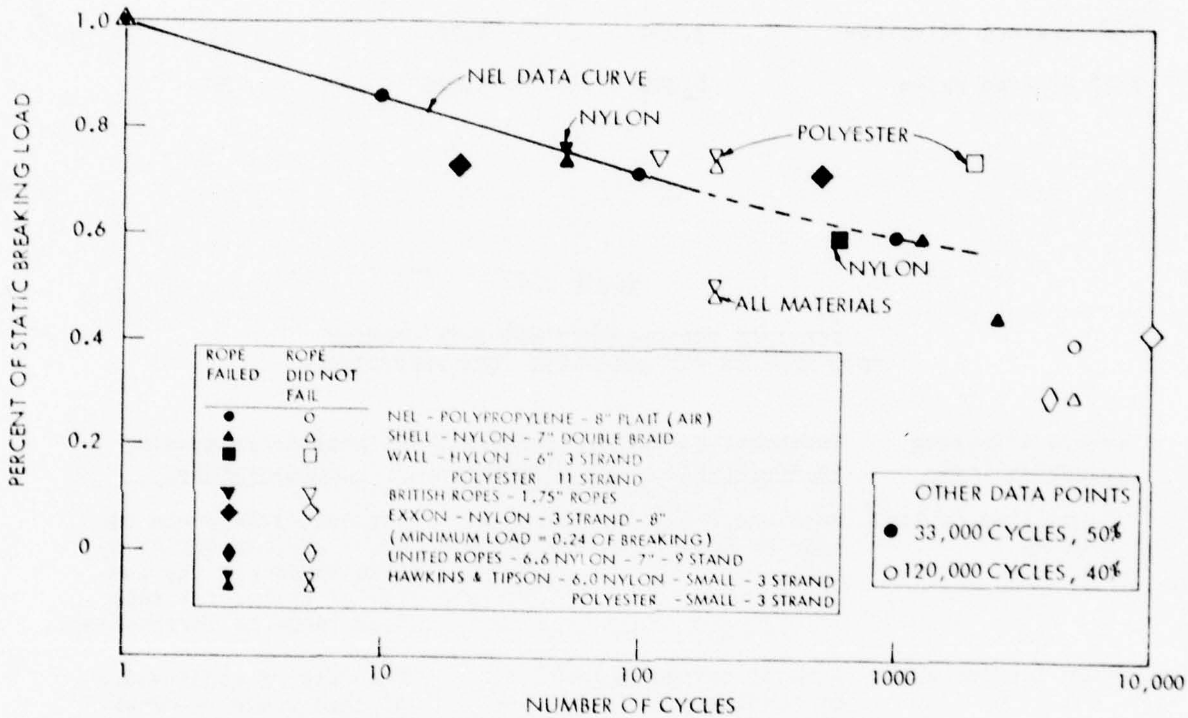


FIGURE 8-1 - DATA FOR CYCLIC LOADING OF SYNTHETIC ROPES

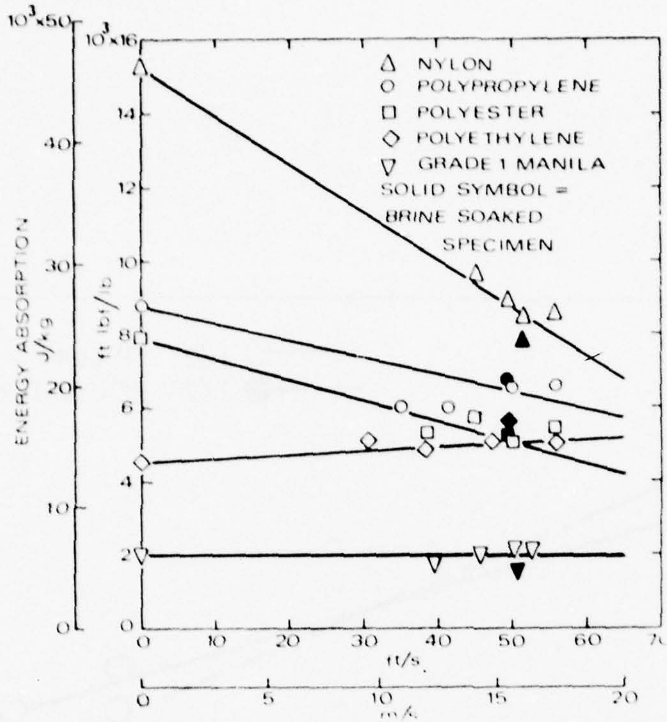


FIGURE 8-2 - BREAKING LOAD FOR SMALL MARINE HAWSERS; THE FIRST RESULTS OF TESTS MADE AT THE NATIONAL ENGINEERING LABORATORY

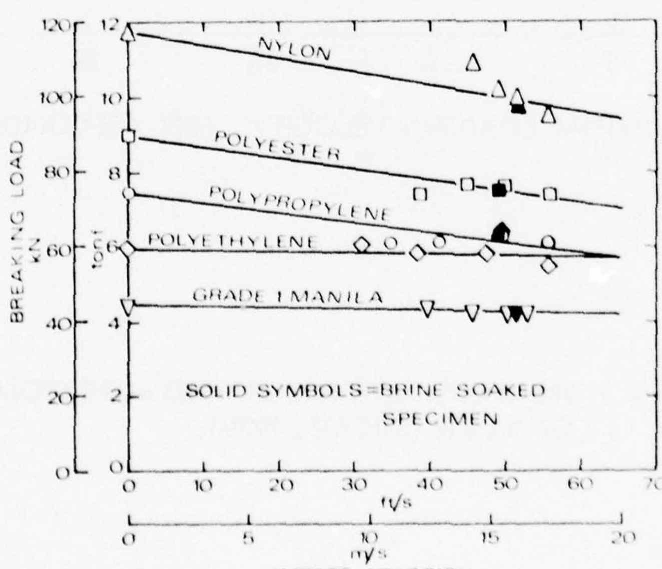


FIGURE 8-3 - THE RESULTS OF TESTS FOR ENERGY ABSORPTION

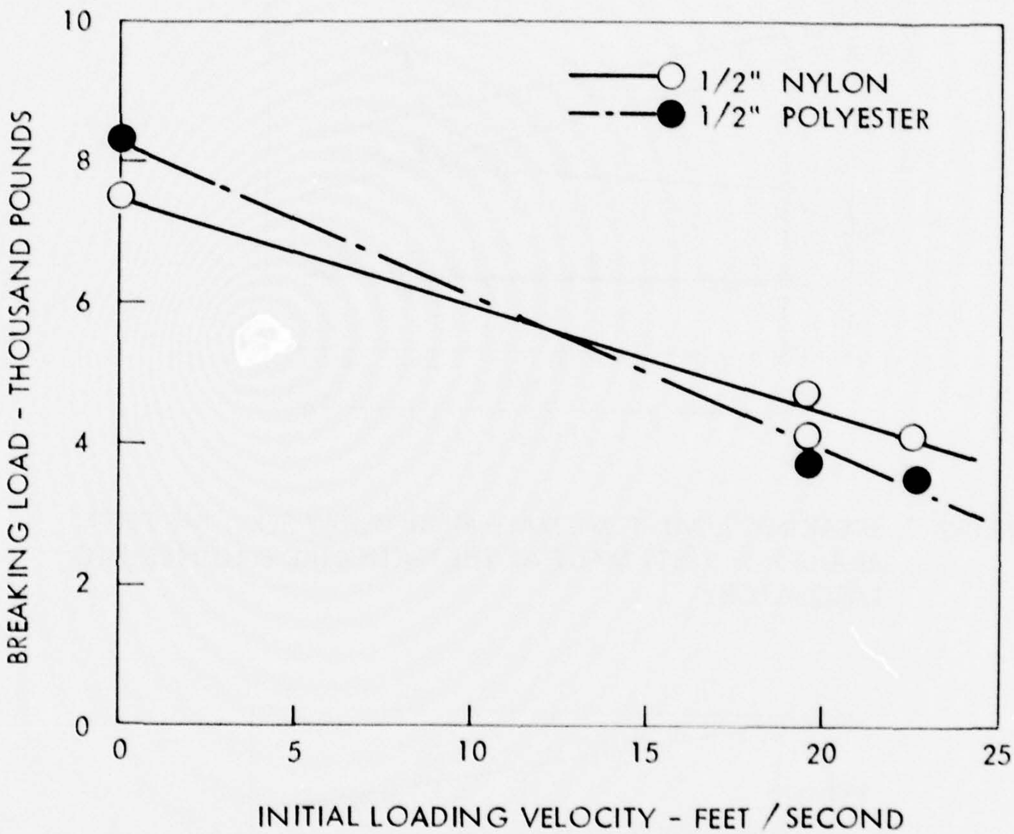


FIGURE 8-4 - BREAKING DATA FOR BRAIDED ROPE FROM DATA OF DICKIE (DICKIE, 1975)

SECTION 9

CRITERIA FOR SHIP MOORING AND UNMOORING

Existing DWP's have developed their own criteria for determining the conditions under which a ship may moor at the port or the conditions at which the ship should leave the mooring (unmoor). The latter criteria may not be the same as that used for termination of cargo transfer operations.

The decision on whether to permit a ship to dock at a DWP will be made by the ship's master and the mooring master assigned to the particular mooring in question or other designated DWP personnel. The decision on when a ship leaves a mooring will be made by the ship's master. DWP personnel may recommend that the ship leave the port, and if this recommendation is not accepted, the DWP may exert pressure on the master, perhaps through the ship's owners. It is considered highly unlikely by port operators that a ship's master would ignore recommendations or pressure from the DWP.

Present criteria for permitting a ship to moor are usually based on the maximum significant wave height (usually six to ten feet) in which mooring launches can operate. Mooring may be prohibited even when launches can safely operate, however, if the weather is predicted to deteriorate to a point where early termination of the mooring is expected. At present, such decisions are probably made on a very subjective basis, the mooring master's experience and prudence being relied upon for safety.

A decision on whether to permit a ship to moor may also be based on initial examination of the ship's mooring fittings by the mooring master who boards the ship. Based on the dis-

cussions in the Exxon Phase I report (Flory, et al., 1977), this examination is considered a necessary prelude to the granting of permission to moor. The difficulty of rational evaluation of mooring fitting strength through visual inspection, as discussed in Section 8.4, is great.

Existing DWPs establish their own criteria, based on wind and wave conditions and/or on measured mooring loads, for recommending that a ship leave the mooring. When a MLMS is in use, excessive mooring load may be the primary criterion. Even with a MLMS, however, the port may establish criteria based on maximum allowable wind speed, wind direction and/or significant wave height. Wind direction is important when the wind is likely to blow a departing ship toward any nearby moorings or fixed structures, such as an offshore platform.

Allowable combinations of wind speed/direction and wave height vary widely. At one North Sea DWP, wind speeds as high as 25 to 30 knots and significant wave heights as large as 25 to 30 feet are permitted. At another North Sea DWP, with a MLMS, ships have been permitted to remain at the mooring and to continue cargo transfer up to combined wind speeds and significant wave heights of 53 knots and 23 feet and 30 knots and 28 feet, respectively. Such criteria are clearly related to measured mooring loads and observed ship motions as well as the design of the particular mooring and the adverse nature of the North Sea environment.

The criteria discussed above are clearly less conservative that the preliminary proposals of LOOP (LOOP, 1976) and Seadock (Seadock, 1976), which call for termination of cargo pumping with 12 foot significant wave heights and departure from the port with 15 foot significant wave heights or hawser loads

approaching the safe working load. Based on operating experience at other DWPs, it seems likely that U. S. DWPs will propose to use the MLMS and the MLPS, if installed, plus environmental factors to determine when a ship must leave the mooring.

One of the important uses of a mooring load prediction system, if installed, will be to provide information necessary for a rational assessment of when a ship should be permitted to moor and when a ship should leave the mooring. Long term predictions will probably be required for decisions on whether to permit mooring. Either long-term or short-term predictions can be used to make decisions on when the ship must leave the mooring. The use of an MLMS should permit a more logical and orderly decision on when to initiate the unmooring sequence.

SECTION 10

RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

In the Exxon Phase I report (Flory, et al., 1977) four topics dealing with the strength of ropes were recommended for further research. These are:

1. Establish test procedures for large-diameter synthetic ropes.
2. Develop large-diameter synthetic rope properties.
3. Develop non-destructive means and practices for determining new-rope strength.
4. Develop means and practices for determining used-rope strength.

These topics are still considered of great importance. Based on the research carried out in the present study, five additional areas are recommended for further investigation:

1. Determine the dynamic strength of new and used synthetic rope.
2. Consider the impact of unique features of LNG ports on MLMS and MLPS requirements.
3. Develop criteria for ship mooring and unmooring requirements.
4. Determine the ambient acoustic environment for SPMs.
5. Develop empirical mooring load prediction methods.

These additional recommendations are discussed in detail below.

10.1 DYNAMIC STRENGTH OF ROPE

In the Exxon Phase I report (Flory, et al., 1977) various factors affecting the strength of synthetic rope and requiring

additional work were considered. The effects of dynamic or shock loading involving high rates of loading were not, however, considered in detail. These effects are considered in Section 8 of this report where it is concluded from the very limited data available that rope strength may decrease rapidly with increasing rate of loading.

It is considered essential to obtain more information on the effect of rate of loading. It may be possible to obtain additional information from rope manufacturers. Facilities for tests of large-diameter ropes do not appear to exist; the specially designed facility at the National Engineering Laboratory (Borwick and Elliot, 1972) can test ropes only up to about three inch circumference. Tests of somewhat larger ropes may be possible using drop tests (Dickie, 1975).

10.2 SPECIAL CONSIDERATIONS FOR LNG DWPS

This study has primarily addressed oil DWPs. The unique factors associated with other DWP cargoes are considered only briefly. Some aspects of LNG terminals, determined primarily from a recent study (Tatge, et al., 1977), are discussed in Appendix G. It appears likely that any LNG DWP will use floating facilities and one or more moorings. Since LNG presents different operating problems than oil and presents potential safety problems, an analysis of mooring load monitoring and prediction systems requirements for LNG DWPs is recommended.

At present, no LNG DWPs or contracts to build such DWPs exist (Tatge, et al., 1977). DWP concepts have probably been developed in sufficient detail, however, to make a limited study meaningful.

10.3 CRITERIA FOR SHIP MOORING AND UNMOORING

Mooring load monitoring and prediction systems will be used to make operational decisions such as whether to permit a ship to moor or whether to recommend or require a ship to leave the mooring. It is assumed that the Coast Guard will establish criteria or will approve criteria proposed by a DWP for such key operating decisions. In order to carry out these functions it is necessary to provide a basis for such criteria.

Criteria for conditions under which a ship will be permitted to moor at a DWP or will be required to leave the mooring are discussed in Sections 4.8 and 9,where some current criteria are quoted. Such criteria can be based on measured hawser loads, existing or predicted environmental conditions or a combination of these factors. Existing DWPs have developed criteria based on their experience.

In order to establish the basis for rational criteria, it is recommended that representative, existing DWPs, and particularly those with MLMSs, be surveyed to determine their criteria for mooring and unmooring and the rationale for these criteria. The results of this survey should then be carefully analyzed to relate existing criteria to proposed U. S. DWPs.

10.4 AMBIENT ACOUSTIC ENVIRONMENT AT SPMS

It is concluded in Section 5 that the most practical transmission system for a SALM MLMSs is an underwater acoustic system. Unless a buried cable is used,minimum transmission distance will be about one-half mile. With this range, there is a danger of significant loss in accuracy if the environment around the SPM is noisy. Existing data on typical background noise is rather conflicting. Noise might be a problem even when a cable is used.

Since there is a good possibility that SALMs will be used or preferred for a U. S. DWP, it is recommended that good data on the acoustic environment around SPMs and large data buoys. at proposed DWP sites be obtained. Tests should be conducted at various depths and in various wind and wave conditions, and over sufficiently long periods of time to insure statistical validity.

10.5 DEVELOPMENT OF EMPIRICAL PREDICTION METHODS

Based on the limited analysis described in Appendix D, it is concluded that useful empirical methods for predicting short- and medium-term SPM hawser loads can probably be developed. Further development and validation using a larger body of data is needed to determine the expected accuracy and utility of such methods. Both model test and DWP mooring load data could be used.

It is felt that a considerable amount of usable mooring load data for existing DWPs can be obtained. Usable data must contain, in addition to load time histories, the ship, wind speed, wave height and perhaps current speed.

SECTION 11

CONCLUSIONS

Based on the results of this study, a number of conclusions seem worthy of special note. These conclusions are discussed below:

11.1 MOORING LOAD MONITORING SYSTEMS (MLMS)

1. All U. S. DWPs should have an MLMS.
2. This MLMS should have the following capabilities and characteristics:
   - o A display of load time history covering at least one hour should be provided.
   - o Aural and visual warning devices should be provided at the control center and on the ship.
   - o Voice radio communication should be provided between the control center and the ship.
   - o The load sensor should be at the buoy end of the hawser.
3. The most critical component of the MLMS is the buoy-control center transmission link.
   - o For CALMs and towers a well designated radio link should be reliable and is recommended.
   - o For SALMs an underwater acoustic link is recommended, but there are potential problems with signal corruptions and a relay will probably be required unless an acoustic/cable system is used.
4. Overall MLMS accuracy should be five percent.
5. Overall MLMS maximum frequency response should be 0.5 Hertz.

11.2 MOORING LOAD PREDICTION SYSTEM (MLPS)

1. A MLPS is not required for a U. S. DWP, due to the short times required to terminate oil transfer operations, but it is recommended that an empirical short- or medium-term MLPS be used at a DWP.

2. It seems feasible to develop empirical methods which have adequate accuracy and which

   o Have modest computer hardware and software requirements.

   c Can be updated and improved as operational data are obtained.

3. Careful processing of measured load data is required for empirical MLPSs.

4. Long-term (six to 48 hour) MLPSs are not required and suitable predictional schemes will be difficult to develop.

5. Methods for predicting wave heights, required for any MLMS, are available, but may impose significant computer hardware and software requirements.

11.3 ENVIRONMENTAL MEASUREMENTS

1. Measurements of wind speed and direction, current speed and direction, and wave height are required for decision making.

2. Measurement of wave direction is desirable but not required.

3. Weather predictions and a means for predicting future wind speed and wave heights are needed for any MLPS.

11.4 DWP OPERATIONAL FACTORS

1. Hawser loads, rather than buoy mooring loads, should limit DWP operations.

2. Allowable hawser loads depend on synthetic rope properties and may be significantly reduced by high loading rates.

3. There is a need to establish criteria, based on hawser loads and environmental conditions, for determining when to permit mooring, to terminate cargo transfer operations and to leave the mooring.

11.5 TYPES OF DWP

1. SALMs offer greater difficulties for MLMs than do CALMs, towers or alongside moorings.

2. LNG DWPs will probably use floating platforms and will probably be quite different from oil DWPs.

APPENDIX A

DESCRIPTION OF ACTUAL LOAD MEASUREMENT SYSTEMS IN USE

During this study five companies were found which have built and/or are building mooring load monitoring systems or sensors. The companies and type of equipment offered are:

OTS/BHC	Complete systems for CALMs, SALMs and Alongside Moorings
Strainstall Ltd.	Complete systems for CALMs, SALMs and Alongside Moorings
Automatic Power	System including sensor and flashing warning lights on SPMs (have supplied some radio equipment)
IHC	Sensors, Flashing Lights
Interstate Electronics Corporation	Building system for Exxon Hondo Field SALM facility

The first two companies, British Hovercraft and Strainstall Ltd., have provided the most complete systems and components. Automatic Power has installed three systems and is about to install a fourth system (see Table 3-1). The number and types of systems installed by IHC are not known, but two IHC sensors are listed in Table 3-1. Interstate Electronics is providing only the electronics package.

Sales literature and sketches of sensors are provided in this appendix. This does not constitute endorsement of any manufacturers product by HYDRONAUTICS, Incorporated or by the USCG.

A.1 MOORING LOAD MONITORING, A RE-APPRAISAL OF MOORING TECHNIQUES

A brochure "Mooring Load Monitoring, A re-appraisal of Mooring Techniques" by J. D. Campbell was provided by Strainstall Ltd. It is included as appendix A.1. The Strainstall Ltd. Shear Pin Load Cell is shown in Figure A-1.

MOORING LOAD MONITORING

A re-appraisal of Mooring Techniques

I. D. Campbell
Marine Manager, Strainstall Ltd

Until recently almost all systems development in tanker design has been directed towards improving the economics and safety of operation of the vessel whilst underway on the open sea, but the same aspects relating to the vessel in harbour have been neglected. It is in the harbour that the large vessel, unable to manoeuvre independently, is more vulnerable to damage through the action of rough weather than when at sea.

Despite the advances of the last twenty years, today's VLCC is secured to its marine terminal berth in substantially the same manner as all other vessels have been secured to their berths for the preceding 1,000 years. Lines supplied from the vessel are passed ashore and secured to fixed mooring points. As the size of the vessels has increased the tendency has been to moor them with a greater number of lines capable of taking heavier mooring loads. However, practical considerations of handleability determine the maximum size of ropes that can be used for mooring large vessels; in general rope performance has not increased proportionately with vessel size because of this restriction. Therefore, margins of safety have been eroded.

The fallibility of this method of vessel restraint has been repeatedly demonstrated by the number which have broken out from their moorings under the single or combined actions of wind, waves and tide; however, the fault is not necessarily in the ropes or configuration of the mooring pattern employed, but in the almost complete deficiency of well-founded information upon which techniques of safe mooring management may be based.

It is established that for many metals increased strain rates produce increased yield points in conjunction with decreased ductility—in mild steel the yield point may be shown to increase by 50% for a substantial increase in strain rate.[1] Bulk plastics and some fibres used in rope construction display similar characteristics.[2, 3, 4] However, it has been thought for some years that ropes, and in particular synthentic fibre ropes in those forms of construction in general use today, did not share these characteristics. The available evidence now clearly supports this theory, namely that a rope subjected to a dynamic loading is appreciably weaker than its stated breaking load may suggest.

The relevance of rope performance under dynamic loading to a vessel secured to a berth in the conventional manner is that such a combination constitutes a dynamic system, a fact which is generally unrecognized. A common misconception is that a mooring line has to withstand force and only force (hence the practice of quoting a rope in terms of its breaking load); this is only true in the quasi static condition. The primary function of the mooring line is to absorb energy, ie to remove the motion from a vessel, however induced, and return it to a state of rest. Logically, if the vessel does not have any forces acting on it capable of inducing horizontal motion, there is no requirement to moor it. In real terms, however, the forces generated by the action of wind, tide and local water disturbances, (eg a passing ship), can be very high, and the energy thus liberated is manifested in the vessel's movement. Therefore, if the vessel is to remain moored and not break out, the mooring system must be capable of absorbing this energy, ie preventing any motion or at worst restricting it, before attaining its point of failure.

It is natural that if all the mooring lines are slack, the vessel has greater freedom to move than if they were bar taut. The vessel is, therefore, permitted to gather way, acquiring kinetic energy as it does so. Consider the energy equation E (kinetic) = $\frac{1}{2}$ MV², where M is the mass of the moving object and V its velocity. In the context of the VLCC, it is obvious that V does not need to have any significant value, when M can be so great, before the mooring system is called upon to absorb very considerable levels of energy. Any mooring line which displays an observable catenary, is, by definition, slack, and so the vessel is free to move more or less unrestrictedly until this slack is taken up. At this point, the mooring line will commence to absorb energy, the level of which will have been amplified by the movement of the vessel. Typically, a mooring line supplied by a VLCC will comprise a 5$\frac{1}{2}$-in circumference wire bent to a 10-in circumference synthetic tail. Over an unsupported length of 120 ft, the catenary will cease to be observable when the line is subjected to a tension of 8 tonf.

It would be reasonable to consider that the function of energy absorption is distributed equally between the members of the mooring pattern. In practice, this is not so. Full scale mooring load measurements carried out by the National Engineering Laboratory, East Kilbride, in association with the Esso Petroleum Co Ltd demonstrated that 95% of the total mooring load was being taken by not more than three mooring lines out of a mooring pattern total of up to twenty. Changes in wind and tide caused load re-allocations amongst the individual lines, but essentially the vessel was effectively restrained by a maximum of three lines at any one time. The mooring system is therefore poorly placed, with 85% of it redundant, to absorb the energies which may be released through surge forces acting on the vessel which the system is securing to its berth.

It therefore follows that any efficient mooring pattern must be comprised of lines of uniform materials and construction, as different materials and lays produce ropes of differing properties in terms of strength, elasticity and energy absorption. Additionally it may be considered inadvisable to equip a large vessel with a 100% synthetic mooring line complement (as distinct from wire with synthetic tails), as the greater degree of elasticity will still allow the vessel to move even when the line is working well up its working range.

In consequence, it is now proposed that, for safe mooring, all lines should be maintained at a minimum tension of (typically) 8 tonf. However, a line not displaying an observable catenary can be at any tension between the 8 tonf and its breaking load. (An experienced man may be able to judge the tension in a mooring line by its "feel", but the increases in the size of the ropes now used has made this method less of a reliable guide.) By tradition, the seaman will tend to ease his lines, but by slackening down, he has provided the vessel with scope to move, thereby worsening the

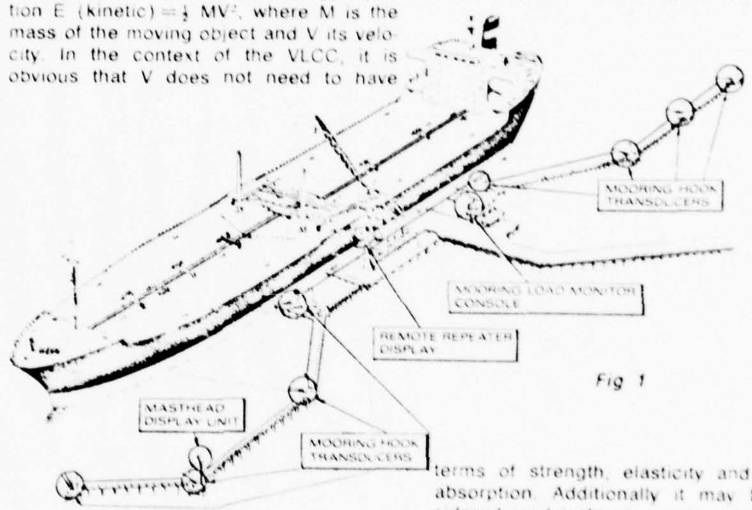
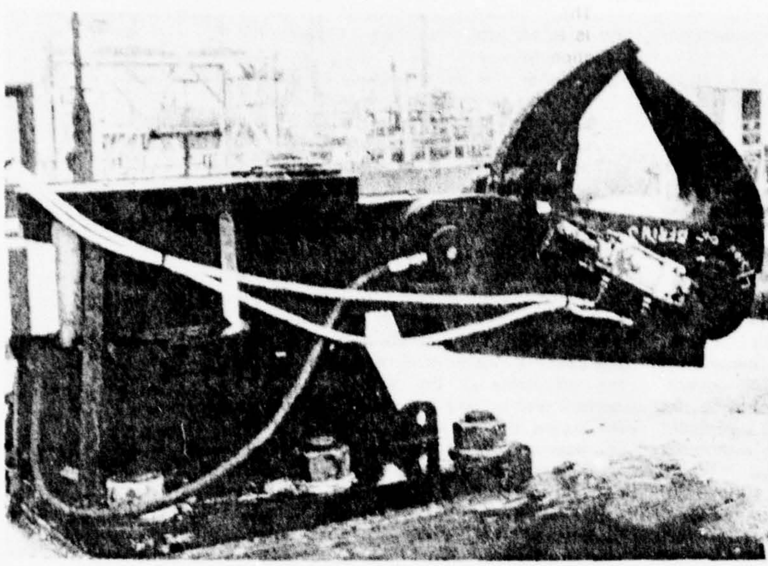


Fig 1



▲ *Fig 2*

situation. Thus there is a requirement for a system which will enable each of the mooring lines to be pretensioned to acceptable and equal values of mooring load, and to detect any radical departures, both above and below the pre-set value, which may affect any particular line or lines. The Strainstall Mooring Load Monitor has been developed for this purpose.

The Mooring Load Monitor (MLM), in its present form, is a jetty installation, and a typical VLCC berth layout is illustrated in Fig 1. However, its techniques could be applied equally effectively to ship-borne winch equipment.

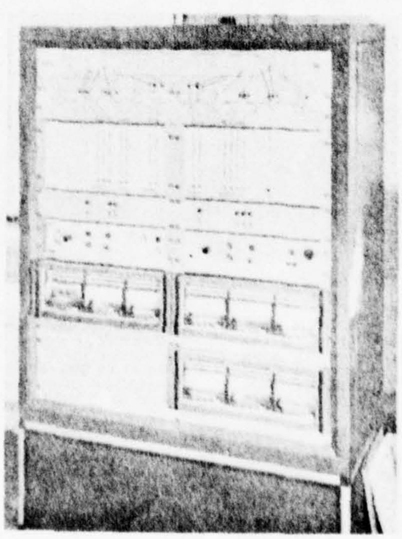
The basic MLM consists of two sub-units:

i) the transducer (Fig 2)—the load measuring device, one being incorporated into the structure of each mooring point; mooring points on large tanker berths are invariably quick release hooks, pulleys or their derivations;

ii) armoured cable connects the transducers to the mooring load monitor console (Fig 3) on which the individual mooring loads exerted on each mooring point are collectively displayed in either histogram or vertical edgemeter format.

In general the transducers are designed to replace an existing member within the hook or pulley assembly through which the total load imparted by the mooring line may be considered to act. This approach obviates any requirement for additional components or structural modifications, and the member generally selected is the horizontal swivel pin, journalled in both the hook pedestal structure and the side plate assembly, which is placed in a condition of double shear when the hook or pulley is under load. The active elements of the transducer are electrical resistance straingauges which produce a voltage output proportional to their degree of deformation when under load. A signal conditioning unit is associated with each transducer and mounted locally to it. Its purpose is to render the load signal insensitive to external electrical interference or degradation of cable insulation resistance, and to maintain the signal level irrespective of the length of cable employed between mooring point and load monitor console position.

▼ *Fig 3*



The central monitor console is installed in the control room of the terminal or control building where it can be under continuous surveyance while a vessel is on the berth. The histogram display facilitates rapid visual comparison of the individual mooring line loads whilst the watchkeeper is able to relate indicated inconsistencies on load data to specific mooring points by means of the leader lines and mimic diagram. Any mooring line load in excess of the set maximum (variable between 25 and 75 tonf) will activate both the audio and visual alarms within the console cabinet, as will any load falling below the nominal 8 tonf minimum. The alarm system circuitry may be employed to activate additional alarms at alternative external locations should the control room not be manned continuously. Permanent records of the load data can be obtained by incorporating paper trace or magnetic tape recorders into the lower racking of the monitor console. It is usual for the recorders to be activated by any excessive variations from the expected load mean (which may not be sufficient to activate the alarms) and to operate for a fixed period, say 15 minutes. Should the load abnormality still persist, the recorders will continue for a further fixed period; if not they will switch off. Continuous running of the recorders, particularly in periods of calm weather, would prove unnecesarily wasteful and costly.

The load information may also be displayed remotely from the control console by means of portable slave readout units (Fig 4). Typically a slave unit could be located at the gangway head, in the vessel's control room or in the berth office. Additionally, the information may be displayed on masthead digital units mounted adjacent to the mooring points to which they refer, as a means of assistance to the winch operators when either slackening down or heaving in.

Total breakouts of large vessels are not common, averaging less than ten per year in UK ports. Partial breakouts are more frequent, and a minor mooring incident occurs almost daily. However, the financial consequences of any mooring accident may prove to be extensive, and may reflect some or all of the following factors, in whole or part:

i) additional use of tugs to hold the vessel under control following a partial or total breakout;

ii) drydocking for hull inspection and possible repair following either collision or grounding, causing with-

drawal from service and consequent loss of earnings.

iii) damage to jetties and dock structures: oil loading/unloading arms are particularly vulnerable.

iv) disruption of an entire port complex by the obstruction of the main navigation channel following grounding, thereby incurring high costs to the port and delays to other shipping;

v environmental pollution through ruptured cargo or bunker tanks:

vi) major risk of fire, particularly in the case of either crude, product or LNG carriers.

Not every berth receiving vessels of large tonnage requires an MLM—operational histories may show that it is not warranted. However, the four significant factors to be considered when evaluating an installation proposal are:

a) whether the berth is subjected to severe meteorological or oceanographic disturbances;

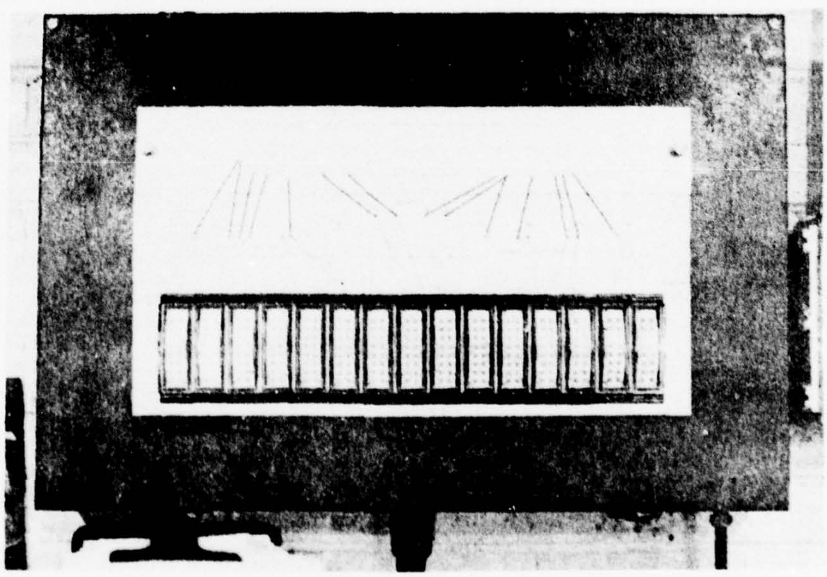
b) whether the volume and tonnage of passing shipping is sufficient to create significant surge forces in the mooring patterns of ships secured adjacent to the main navigational channel;

c) whether the density of other oil/gas carrying vessels in the port area is such that the potential hazards of a breakout are greatly increased;

d) whether loading/unloading restrictions dependent upon (a) and (b) above may be relaxed as the vessel is now secured to its berth under a greater degree of control.

The Mooring Load Monitor can make a major contribution to future port safety. The information it provides enables the terminal superintendent or the vessel's master to assess continuously the efficiency of the vessels' mooring pattern and to take the necessary actions to ensure that maximum mooring safety is maintained. Significant operational economies can result from the improved use of berthing time and the lessened requirement for stand by tugs during periods of uncertain weather, while the risk of a total or partial breakout is greatly reduced.

▼ *Fig 4*



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A.2 A TYPICAL MOORING LOAD MONITORING SYSTEM (TECHNICAL DESCRIPTION AND SPECIFICATIONS)

A copy of a sales brochure (Ocean Technical Services and British Hovercraft Corporation) describing mooring load monitor for both CALMs and SALMs is included as Table A-1. The BHC tensile cell is shown in Figure A-2. Table A-3 lists specifications for BHC radio intended for CALM use. Finally, Table A-4 lists some specifications for a BHC acoustic link intended for SALM use.

A.3 MISCELLANEOUS EQUIPMENT INFORMATION

Figure A-3 is a sketch of a load cell provided by Automatic Power Incorporated. This is the unit installed on the Imodco CALMs and listed in Table 3-1.

Interstate Electronics Corporation is currently building a sophisticated data processing system for use in monitoring riser and mooring yoke loads for the Exxon Hondo Field SALM production system. This data processing system receives load data from various strain gage sensors and can provide a wide variety of CRT data outputs for mooring loads,ship or platform motions and environmental data. Table A-5 shows a typical CTR summary output for a one-half hour period for a platform with a 12 point mooring. In the Hondo Field system data are transmitted by electric cables to the data processing unit which is located on the production ship. Data for the riser loads is transmitted through an induction or magnetic coupling located at the SALM buoy.

During this study no other U.S. companies were found who had actually built and installed mooring load monitoring systems or equipment which was suitable for DWP use. Several

companies who manufacture load cells and/or cable tension measurement equipment for other marine use are listed in Table A-6.

Since acoustic transmission appears to be the only viable technique for use with SALMs such as proposed for the LOOP Incorporated DWP, literature describing an off-the-shelf acoustic telemetry is included in this appendix as Table A-7. This is an AMF unit which may or may not be suitable for DWP use, but the specifications (particularly for accuracy, temperature and battery life) are typical.

TABLE A-1 - BHC SALES BROCHURE

Buoy load monitors provide vital information on the safety of vessels on offshore terminals.
The monitors are designed to measure the load in the mooring lines and can supply the following information:—

> **Continuous Indication of Mooring Line Load/Audio and Visual Alarm, when load exceeds a pre-set value/**
> **Permanent Chart Recordings of Loads, thus providing historical data on rope fatigue and operational conditions.**

During operational use of the system the chart recorder can be used to display the trends of load changes.
The telemetry link, which is an integral part of the monitor can be used in conjunction with other transducers to provide continuous information on:—

> **Hose Pressure/Buoy Attitude/Anchor Line Load/Battery Condition/Pollution Detection Sampling.**

In addition the link can also be used for remote service functions such as:—

> **Operation of the Manifold Valves/Switching of Fog Horn System/Product Flow Rate.**

For hazardous locations BASEEFA certification can be supplied for the system.
To meet today's design needs systems are available for use both on CALM buoys and single anchor leg moorings (S.A.L.M.).

CALMonitor

A typical system consists of a strain gauged load cell and a UHF radio telemetry link which transmits encoded signals of the load cell output to a shore station and/or tanker.

The **Load Cell**, which produces an electrical signal proportional to the load applied, can either be of the in-line tensile link type or of the shear pin variety. In general the operator would be advised as to the suitability of each type for the installation but the shear pin arrangement is usually preferred, because of its compact design and low weight which enables it to be fitted into most existing mooring arrangements.

All load cells are proof tested to 150% maximum safe working load and supplied with a Lloyds certificate of calibration.

The **On-Buoy Unit** comprises a power supply in the form of a battery pack, the size of which is dictated by the operational requirements of the buoy and the necessity for a minimum life of say 3 months. The normal batteries used are of the air depolarised type and storage of the batteries on the buoy is designed to meet safety standards. Also located within the battery enclosure is the transmitter/receiver unit incorporating the encoder modules. A small omnidirectional aerial is usually attached to a suitable structure on the buoy.

The **Shore-Based Receiver** processes the signals from the buoy which are then displayed on a strip chart recorder and/or meter. Also included in this unit are the required alarm systems. The cabinet dimensions are dictated by the number of monitors and service functions required by the operator. The unit can be supplied either in a free standing cabinet or for existing rackings and is designed to operate from the local power supply.

A **Portable Receiver Unit** is available for the mooring master to take on board the tanker. This unit contains a meter for the indication of the mooring line load, and is also fitted with an adjustable alarm system. Power supply for this receiver unit is in the form of rechargeable batteries and the unit is both rugged and splash proof.

The **Operating Frequency** normally used is in the 450-470 MHz band. The licence is obtained from the local telecommunications authority by the operator and any technical assistance required to obtain this can be provided. The majority of the on-buoy power is consumed by the transmitter units and to conserve battery life it is advisable to de-activate the system when not in service. Three **Battery Conservation Switching Systems** are available,

- manual, requiring personnel to board the buoy, low
- level, in which the transmitter is de-activated for loads below say 10% of the nominal maximum, and
- remote activation of the transmitter from the shore base.

Battery Low Voltage Warning is also available which automatically signals a pre-set minimum power level in the battery pack. This level would normally be sufficiently high to enable operations to continue for some time prior to replacing the batteries.

SALMonitor

In this system, the load and buoy heel angle information is transmitted to the tanker via underwater acoustic telemetry and is displayed on a recorder on board the tanker. An alarm system is incorporated which is activated when a pre-set load level or heel angle is exceeded.

The buoy is fitted with a load cell, signal conditioner unit, acoustic telemetry transmitter and an inclinometer, all of which are designed to operate fully submerged.

The **Load Cell** for this type of installation is a specially designed, patented, shear pin which, together with its electronic circuitry, always senses the true load in the mooring line irrespective of the buoy heel angle. All load cells are proof tested to 150% maximum safe working load and supplied with a Lloyds certificate of calibration.

The **On-Buoy Electronic Unit** conditions the input signals from the load cell and the inclinometer and generates the acoustic output. The unit is contained within a protective case which is designed to comply with safety regulations.

Where possible the existing buoy **Power Supply** will be used. The power requirements for this system are 12v DC at 100-200 mA. Where adequate power supplies are not available a supplementary battery pack can be supplied.

The equipment has an **Operating Frequency** of 4KHz with a directional transducer beamed towards the tanker. The **Acoustic Transducer** is located on the casing of the buoy at a level of approximately 30 metres below sea level. This depth allows a reasonable inspection time or refit for a diver without decompression.

A **Switching System** for the electronic unit and load cell is designed to commence acoustic transmission when it detects a signal greater than that expected to be produced by the tidal drag on the unattached mooring lines.

The **Tanker-Borne** equipment consists of a locally deployed hydrophone, receiver/decoder and load/heel angle display.

The **Hydrophone** is deployed as close to the bow as possible, from a portable derrick and winch unit whenever the vessel is on the mooring. The depth of deployment should be sufficient to ensure that the hydrophone, which will be ballasted to reduce streaming, is approximately 7 metres below the keel of tanker.

The **Receiver/Decoder Unit** processes and feeds the signals from the buoy to the display on the strip chart recorder and/or meter. Also included in this unit are the required alarm systems.

All systems are guaranteed for a period from the date of installation against materials and workmanship. The electronics of the system are designed on a modular principle so that component failure is rectified by unit replacement. A comprehensive after sales service is available.
Operators will have varying requirements for buoy load monitors and systems can be designed with various options to suit the needs of different terminals for new or existing installations.
The use of buoy load monitors has to date led to substantial improvements in the utilization of the buoy during marginal weather conditions.

TABLE A-2

SPECIFICATIONS FOR BHC SENSORS

TECHNICAL DATA

Mechanical	Typical working load*	500 tons
	Lloyd Prrof test load	750 tons
	Theoretical breaking load	2000 tons
	Load cell material	EN24Y heat treated to 65 ton/sq. in. UTS
	Weight of Shear Pin	70 lbs. (32 kg)
	Weight of Tensile Link	13 cwt (660 kg)
Electrical	Strain gauge bridge resistance	700 ohms
	Strain gauge supply voltage	10 VDC
	Strain gauge supply current	14 ma
Accuracy	Inaccuracy due to combined effects of hysteresis, non-linearity and temperature between 10° and + 30°C	Better than $\pm 1\%$
Safety Approval	For use in hazardous areas	
	Tensile Link Load Cell	BASEEFA approved to SFA 3009:1972
	Shear Pin Load Cell	BASEEFA approved to BS4683: part 3:1972

*Determined by customer requirements.

TABLE A-3

SPECIFICATIONS FOR BHC BUOY

ENCODER/TRANSMITTER

TECHNICAL DATA

Dimensions	48"x24"x24" (includes a 12 cell battery)
Weight	450 lbs. approx.
Service	F3 modulation: single frequency
Frequency Coverage	450-470 MHZ
Power Output	2 watts-vertical polarization
Temperature Range	$-10^{o}C$ to $+50^{o}C$
Frequency Stability	Not more than ± 5ppm within the temperature range $-10^{o}C$ to $+40^{o}C$
Current Consumption	1 amp maximum
Range	5-10 miles
BASEEFA Safety Conformity	BS 4683:Part 3:1972

TABLE A-4

TYPICAL SPECIFICATIONS BHC ACOUSTIC LINK

Transmission Techniques	1. Data from 2 sets (redundant) of transducers are transmitted on alternate frame basis. In the event of one system failure a 2:1 reduction in data rate will occur. 2. Data transmitted once/second under normal operational conditions. 3. Pulse modulation of a carrier. Information carried as time separation between pulses of differing frequences.
Frequency	40 KHZ (transducer will be moderately directional)
Signal Corruption	Overall system errors on any channel due to signal corruption provide better than 80% data recovery in any one minute period under the following conditions: a. Wind speed up to 33 knots b. Noise levels within the frequency bands used may be up to 20 dB above normal ambient c. Tidal and wind driven current velocity at depths greater than two meters shall not exceed 1.2 knots.

TABLE A-5 TYPICAL CRT OUTPUT FROM INTERSTATE ELECTRONICS DATA PROCESSING SYSTEM

STATISTICS SUMMARY DAY 157/1977 FROM 1530 TO 1600

CH	SENSOR	UNITS	AVERAGE	MAX 1/TIME	MAX 2/TIME	MAX 3/TIME
1	WAVES	FEET	18.5	28.9/1539	28.4/1538	26.5/1531
2	WIND	MPH	34.2	53.4/1535	53.0/1539	45.2/1530
3	WIND	DEG	51.0	52.7/1535	55.9/1539	57.6/1530
4	AIR T	DEGF	26.1	29.5/1553	27.2/1542	27.1/1540
5	HUMID	% REL	49.9	51.5/1555	51.1/1554	50.0/1544
6	BARO P	MBARS	995.3	999.1/1530	998.9/1543	997.5/1548
7	HEAVE	FEET	0.7	1.0/1538	0.7/1533	0.6/1539
8	SURGE	FEET	2.6	3.5/1537	3.0/1530	2.9/1534
9	SWAY	FEET	1.3	2.7/1538	2.1/1531	1.8/1534
10	ROLL	DEG	0.6	1.7/1535	1.7/1530	1.6/1532
11	PITCH	DEG	0.3	0.8/1537	0.6/1555	0.6/1543
12	CURENT	KNOTS	0.1	0.4/1548	0.2/1544	0.2/1559
13	CURENT	DEG	30.9	46.7/1548	33.8/1544	27.6/1559
14	POS'N	%DPTH	0.8	1.9/1544	1.8/1543	1.2/1558
15	POS'N	DEG	340.3	349.6/1544	338.0/1543	341.1/1558
16	RISER	DEG	0.5	0.9/1544	0.7/1548	0.6/1531
17	RISER	DEG AZ	329.6	335.4/1544	330.2/1548	323.0/1531
18	LINE-1	KIPS	337.6	345.2/1538	340.8/1539	339.6/1548
19	LINE-2	KIPS	250.3	267.6/1548	259.9/1555	258.6/1558
20	LINE-3	KIPS	129.7	155.8/1538	149.7/1552	138.3/1532
21	LINE-4	KIPS	186.4	206.3/1542	200.3/1549	193.2/1542
22	LINE-5	KIPS	203.0	225.6/1544	219.7/1531	211.1/1555
23	LINE-6	KIPS	135.6	148.7/1549	144.4/1533	138.6/1542
24	LINE-7	KIPS	258.1	290.4/1557	286.2/1531	280.0/1549
25	LINE-8	KIPS	167.7	199.3/1540	188.2/1532	173.8/1541
26	LINE-9	KIPS	223.9	256.1/1548	244.2/1539	230.0/1537
27	LINE10	KIPS	200.1	222.2/1547	217.3/1541	210.6/1536
28	LINE11	KIPS	138.7	144.4/1548	143.5/1533	142.4/1537
29	LINE12	KIPS	174.4	189.3/1538	186.3/1541	180.2/1555

HEAD'G: 135 MAGN. VAR: 14 DEPTH: 600 DRAFT: 80 WAVE DIR: E
SITE NI: A34 LOCATION: SUE CHANNEL OPER: J. JONES

This report presents averages, maximums and their times of occurrence for a half hour statistics interval.

TABLE A-6

U.S. COMPANIES WHO SUPPLY LOAD CELLS, CABLE TENSION MEASURING EQUIPMENT ETC. FOR MARINE USE BUT NOT, TO DATE, FOR DWP USE

COMPANY/LOCATION	EQUIPMENT OR SERVICE
Bendix Corp., Environmental and Process Instruments Div. Baltimore, Maryland	Environmental Instruments. Also have supplied instrumentation and data acquisition to work with another manufacturers load cell for use on offshore drilling rig.
BLH Electronics, Inc. Waltham, Massachusetts	Strain gages, load cells, transducers and instrumentation.
Dillon W.C. and Co., Inc. Van Nuys, California	Load cells of various types, such as tensile links, hooks, shackles and pins. Also a running line tensiometer.
ENDECO Marion, Massachusetts	Underwater acoustic transponders and telemeters. They have built a special load cell into an anchor chain for 100,000 lb. loads.
ENERPAC Div., Applied Power Ind. Inc. Butler, Wisconsin	Hydraulic equipment and tools for industry. Also load cells.
ENESS Research and Development Co. Westwood, New Jersey	Special made meters for 1-1/2 in. wire cable. Measure tension, speed and travel.
ENVIROMARINE Laurel, Maryland	Marine Systems Engineers. Have made a load cell to measure load in towing cable for ocean bottom sled (10,000 ft.)
Lucker Manufacturing Co. King of Prussia, Pennsylvania	Wire rope jacking and pulling systems. Cable grips, wire rope proof testing equipment. Hydraulic power units with gages.
Martin Decker Co. Santa Ana, California	Wire line tensiometers, system for wire rope mooring lines. Tension and compression hydraulic load cells. Hydraulic crane scales.
Schaevitz Engineering Pennsauken, New Jersey	Load cells and transducers for force, tension and stress. Make LVDT transducers. Have made system for use in water in test laboratories.
STRAINSERT West Conshohocken, Pennsylvania	Load Cells: Shear pins, tension links and strain gaged screw and bolts. Have made system for dry dock elevator. The shear pin is similar to Strainstall unit but gages are inside the pin.

TABLE A-7 - A TYPICAL ACOUSTIC TELEMETER

AMF Sea-Link Underwater Acoustic Telemeters

Remote monitoring of deep-sea data without electrical cables.

The AMF Sea-Link multi-channel acoustic telemeter Model 510A gives continuous shipboard monitoring of four underseas conditions and at the same time reports the occurrence of three separate events—*all without* electrical cables. The Acoustic Telemeter has the advantage of providing near real time information on underwater experiments even while lowering, raising or towing is taking place. This capability eliminates the need to raise associated instruments for checking and detects malfunctions immediately.

Two of the Telemeter's four channels normally are used to give it the built-in capacity to sense and transmit to the surface its own depth and surrounding water temperature. The third and fourth channels, through a marine connector mounted on the housing cap, can be used to transmit data from sensors external to the Model 510A. It can also transmit up to three specific external events—such as bottom contact, camera operation etc. by actuation of external status switch closures linked to the Telemeter through the marine connector. Available options give the AMF Sea-Link Acoustic Telemeter the flexibility to meet specific needs of the user. For instance, sensors other than the standard built-in depth and temperature sensors can be provided.

The Model 510A is a time-sharing, pulse position data telemetry system used to transmit information to a surface ship for display on precision graphic recorders normally carried on oceanographic vessels. In actual practice, a simple overlay is used to read the data. The overlay places the Telemeter's clock mark at zero, the three specific events at 16, 32 and 48 milliseconds, respectively, and the analog data base point at 64 milliseconds with the data maximum at 464 milliseconds. Since the clock pulse is emitted at precise intervals and the pulse for each channel is delayed by an interval that varies with the value of collected analog data, the shipboard data is read directly as the distance between the 64-millisecond base point and each information channel pulse mark. State-of-the-art CMOS logic and hybrid thick film circuitry and ultra low drain analog devices combine to give the AMF Sea-Link Systems Acoustic Multi-Channel Telemeter long life, high reliability and a flexibility that enables it to provide information for a wide spectrum of underwater experiments.

Specifications

Information Channels: Four channels—depth, temperature and two external inputs standard.

Depth Data Range: Standard 3000, 10,000 or 20,000 ft. full-scale depths (specify when ordering). Others available.

Temperature Data Range: 0°C to 30°C or 0°C to 60°C range standard (specify when ordering). Others available.

External Channels: 0 to 4 volts (1 kilohm source).

Time Sharing Format: 2, 2, 2, 4 (2 seconds first three channels, 4 seconds remaining channel). Other formats available.

Data Pulse Delay: 64 to 464 milliseconds after clock pulse in linear relation to inputs.

Data Pulse Delay Accuracy: ±2% of full-scale data reading.

Event Marks: Three switch operable pulses, externally switched.

Output Frequency: 12kHz ±0.1% Standard (7.5 to 15 kHz available).

Acoustic Output: 185 db re 1μPa at 1m, 75° from vertical. Omni-directional within ±3db in upper hemisphere.

Outp.t Pulse Width: 2ms ±10% standard (10ms available or 4ms for reference pulse with data and event pulses at 2ms available).

Clock Period: 1 second ±50 microseconds standard.

Battery Operating Life: 80 hours to half power.

Storage Temperature: −20°C to 85°C.

Housing Depth Range: 20,000 ft.

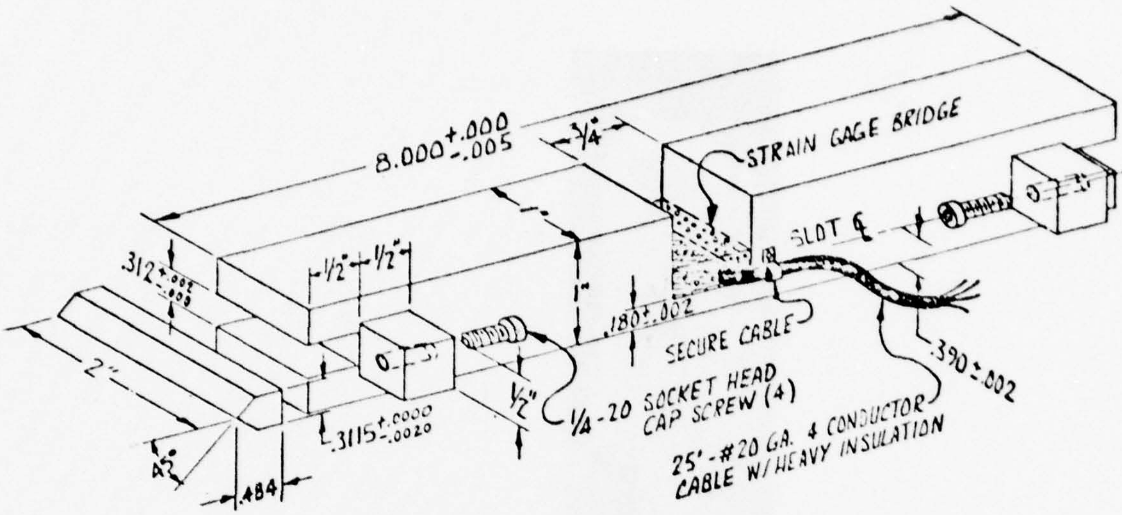
Weight: 18 kg (40 lb.) in air.

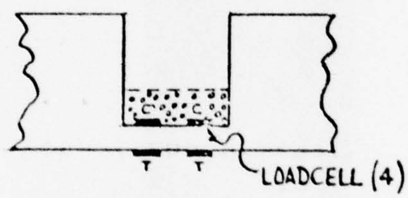
Length: 100 cm (39.5 in.) overall.

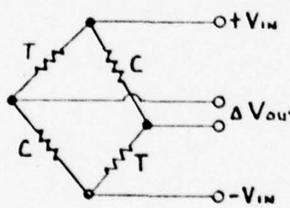
Diameter: Housing 12.7 cm (5.0 in.). Maximum 16.2 cm (6.4 in.).

FIGURE A-1 - A STRAIN GAGED SHEAR PIN LOAD CELL FOR MOORING OR TOW LOAD MONITORING (SOURCE STRAINSTTALL LTD.)

FIGURE A-2 - A 200 TON STRAIN GAGED TENSILE LOAD CELL FOR SPM LOAD MONITORING (SOURCE: BRITISH HOVERCRAFT CORP.)







BRIDGE CHARACTERISTICS

SUPPLY VOLTAGE: (10 VDC/±5 VDC) MIN.
(20 VDC/±10 VDC) MAX.

OUTPUT:

TENSION [kips]	V_o [mV/V]
300	1.00
240 (100% defl.)	0.80
192 (80% defl.)	0.64
144 (60% defl.)	0.48

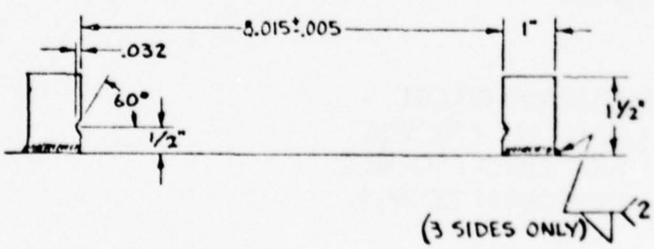


FIGURE A-3 - SPM MOORING LOAD CELL FOR INSTALLATION ON BUOY BEARING MEMBER (Source Automatic Power Inc.)

APPENDIX B

DEFINITION AND DESCRIPTION OF TRANSDUCERS

The IEEE Standard Dictionary of Electrical and Electronic Terms (IEEE Std. 100-1972: ANSI C42.100-1972) defines transducers as "a device by means of which energy can flow from one or more transmission systems or media to one or more other transmission systems or media." Selecting a transducer for a given application can be very difficult because generally there are many transducers which can sense a given variable and every transducer can generally sense several variables. For purposes of this study, transducers are segregated into five basic types (Truxall, 1958). These types are:

1. Magnetic Field
2. Electric Field
3. Variable Resistance
4. Bulk Effects such as Magnetostrictive and Piezoelectric.
5. Miscellaneous, such as control of oscillators, mechanical responses and media changes which produce phase changes, etc.

In a basic transducer the change from mechanical input to electrical output is accomplished directly. Displacement, for example, can be measured directly by a number of different transducers. A potentiometer converts the displacement of a sliding contact directly into a variable resistance. The relative displacement of two parallel plates can convert directly into a change in capacitance (electric field). In a differential transformer the displacement of a magnetic core (magnetic field) is converted into a differential voltage.

Many quantities such as acceleration and force often are measured indirectly by employing displacement transducers with auxiliary masses, springs, levers, etc. Such devices generally can be calibrated to provide accuracies equal to direct measuring transducers. Each of the transducer types listed above are discussed with examples of applications.

The magnetic-field class of transducers includes those devices in which a magnetic field is modified by a mechanical input to produce an electrical output. Some typical examples are variable transformers, variable reluctance devices, self-generating devices and devices which depend on the nonlienar properties of the magnetic materials.

In this class of transducers the voltages are produced by magnetic induction. The steady-state voltages may be expressed as:

$$E = - N \frac{d\varphi}{dt}$$

where E is voltage, N is the number of conducters and $\frac{d\varphi}{dt}$ is the rate of change of flux. If the moving element has a significant velocity, a velocity dependent voltage component will be induced which can be appreciable.

In a variable transformer the primary field remains essentially constant while the coupling into the secondary winding is varied. In variable reluctance devices the field varies due to changes in the magnetic circuit.

Self-generating devices employ a mechanically driven part, such as a coil, which produces a variation of the flux linking the output coil.

Finally nonlinear devices can use the nonlinear magnetization curve of ferrous materials. A superimposed biasing field controls the operating point along the magnetization curve. This produces

harmonics of the fundamental excitation voltage. Another method is to use the saturating characteristics of square loop cores in much the same manner as a saturable reactor. However, in a transducer the d.c. flux is varied mechanically rather than electrically.

Electric-field transducers generally take the form of a variable capacitor. Mechanical motions may either vary the area of or the spacing between capacitor plates. In some transducers, such as fluid level sensors, the dielectric medium changes to produce the capacitance change. It is possible with very high impedance amplifiers to use the voltage gradient directly to ascertain the spacing between two electrodes. This technique has been used, by measuring the gradient in the earth's atmosphere, to make an autopilot for model airplanes.

The most common variable resistance transducers are potentiometers, strain gages and temperature sensitive resistance elements. Potentiometers are resistance elements that have an electrical tap which can be positioned anywhere along the element. The resistance element can be configured for rotary or rectilinear motion and can vary linearly with displacement or describe an arbitrary function. Wirewound potentiometers vary in discrete steps whereas ceramic and metal film devices have continuous elements.

Strain gage refers to the class of resistance transducers which produce a change of resistance in response to deformation of the sensing element due to longitudinal strains. Strain gage elements are generally wire, metal film and semiconductors. Wire and metal film materials are usually from the same class as those employed in potentiometers. Semiconductor gages make use of the piezoresistivity properties of the material. Their major advantage is that very high gage factors ($\Delta R/R_o$) is possible.

This means that much higher output voltage per unit strain are possible. Advances in the technology of gage manufacture, mounting and temperature compensation have produced devices that are very sensitive, accurate and reliable in all types of environments.

Although temperature sensitive resistance elements are not electromechanical transducers, they are discussed here because a rope that is cycled in tension produces heat. The resultant temperature rise could possibly be measured and related to load. The three types of temperature transducers most commonly used are thermocouples, wire elements and thermistors. Thermocouples are not resistive but provide a voltage proportional to the temperature difference across the junction.

Of the metals which could be used for temperature-sensitive resistors, platinum is the best. It has a well-defined resistance vs. temperature relationship. The temperature-resistance relationship of metals is usually defined as

$$R = R_o(1 + A_1T + A_2T^2 + A_3T^3 + \cdots + A_nT^n)$$

where R is the resistance at temperature T degrees centigrade (c), R_o is the resistance at $0°C$, and A_1, A_2, etc. are constants. The first two constants are sufficient to describe the properties of platinum but three are required for copper, nickel and other metals. Platinum also is the most stable temperature-measuring device in the range from $-190°C$ to $660°C$. Finally, it resists contamination.

Two well-known bulk effects that can be used to make transducers are magnetostrictive and piezoelectric. When a magnetic field is applied to a ferromagnetic body, it becomes longitudinally strained. This is called the Joule effect. Conversely, when a longitudinal stress is applied to a magnetized bar, its

magnetic induction is changed (Van Der Ziel, 1957). This is knwon as the Villari effect. This effect is difficult to use in a transducer because nonlinearities are large and comples, and temperature dependence also is great.

In certain materials there is a similar effect where the coupling is between the mechanical stress and the electric field. This is called the Piezoelectric effect. The equations relating mechanical stress and electric field are similar in form to those relating stress and magnetic field in magnetostrictive devices (Van Der Ziel, 1957). The piezoelectric effect is not very useful for displacement transducers because the forces associated with the motion must be large compared to the forces required for deformation of the crystal. It is used, however, for pressure transducers, accelerometers, etc. The chief advantage of these transducers is their high natural frequencies. The chief disadvantage is a rather high temperature sensitivity.

So many transducers have been built that it would be virtually impossible to list and classify them all. The above paragraphs describe some of the basic physical effects which have been used to make electromechanical transducers. It is also possible to use these effects indirectly. For example, a varying magnetic field, which might be mechanically controlled, could be applied to a magneto-resistive material to produce a varying resistance. Resistive, capactive and inductive transducers all are often used to control the frequency of an oscillator. Frequency modulation is very useful when the transduced signal must be transmitted over a large distance by cable, radio or other means.

It is possible to control an oscillator directly by a mechanical input. One example is a plunger in a resonant cavity. Another is a taut wire in a transverse field. The wire, with a

suitable negative resistance connected across it, vibrates at its natural frequency which can be varied by varying the tension.

Finally, the transmission media for radio, light or sound waves may be changed to produce frequency or phase changes. Path length changes result in phase shifts while velocity changes produce the well-known doppler frequency shift.

APPENDIX C

CHARACTERISTICS OF WARNING DEVICES

There now exists considerable data on the effectiveness of various aural and visual devices for warning and for transmitting information to human operators. These data are briefly summarized in the text. It is useful, however, to address warning device effectiveness in more detail, as each situation presents unique conditions which can affect warning device performance.

C.1 VISUAL DEVICES

Table C-1 (from McCormick, 1976) provides a summary of principal factors influencing the effectiveness of visual devices. Table C-2, from the same reference, provides a summary and evaluation of various visual coding methods. It can be seen from Table C-2 that it is possible to provide differentiable messages with all types of devices, but that graphic displays can provide more precise differentiation than can lights. Of particular note, are the potential problems with color displays for certain illumination conditions or for persons with color vision handicaps.

Figure C-1 (from Hemingway and Erickson, 1969) shows the effectiveness of CRT alphanumeric displays as a function of symbol size and scan size. The symbol size is measured by angular substence or size of the visual angle, which depends on physical symbol size and distance of the viewer from the display. There is a trade-off between number of scan lines per

symbol and symbol size, as the number of scan lines on a given display is fixed. It is concluded (Hemingway and Erickson, 1969), that it is desirable to provide 8 or more scan lines per symbol unless symbols are quite large. For larger symbols, 6 to 7 scan lines per symbol is satisfactory. For a viewer-to-display distance of three feet, a 12 minute arc (required for 95 percent accuracy with eight scan lines) represents a one-eighth inch symbol size.

C.2 AURAL OR AUDITORY DEVICES

Table C-3, (based primarily on a table from Deatherage, 1972), presents desirable characteristics of aural warning signals. Table C-4 from that same reference presents characteristics and features of a number of aural warning devices. Of particular interest in Table C-4 are the attention-getting and noise-penetration abilities of various devices.

TABLE C-1

FACTORS INFLUENCING THE
EFFECTIVENESS OF VISUAL DEVICES
(FROM MCCORMICK, 1976)

Color of Lights - Another factor that is related to the effectiveness of signal lights is color. Using response time as an indication of the effectiveness of four different colors, Reynolds, et al. report the following order (from fastest to slowest): red, green, yellow, and white. However, the background color and ambient illumination can interact to influence the ability of people to detect and respond to lights of different colors. In general, the researchers found that if a signal has good brightness contrast against a dark background, and if the absolute level of brightness of the signal is high, the color of the signal is of minimal importance in attracting attention. But with low signal-to-background brightness contrast, a red signal has a marked advantage, followed by green, yellow, and white in that order.

Flash Rate of Lights - In the case of flashing lights, the flash rate should be well below that at which a flashing light appears as a steady light (the flicker-fusion frequency), which is approximately 30 times per second. In this regard, rates of about 3 to 10 per second (with duration of at least 0.05 s) have been recommended for attracting attention. Woodson, Conover, and Markowitz make the point that the range of 60-120 flashes per minute (1 to 2/s), as now used on highways and in flyways, appears to be compatible with human discrimination capabilities and available hardware constraints.

Background of Lights - As might be expected, signal lights cannot be discriminated well when other background lights are somewhat similar. (Traffic lights in areas with neon signs and Christmas tree lights represent very serious deviations from this principle.) And still another background characteristic relates to the steady versus flashing state of any background lights. In an interesting investigation of these, Crawford used both steady and flashing signal lights against background or irrelevant lights (what we might call noise), these being all steady, all flashing, or some admixture of steady and flashing lights. Very briefly, his results indicated that the average time to identify the signal lights was minimal when the background noise lights were all steady (this was especially so when the signal light was itself flashing); that the advantage of a flashing signal light (contrasted with a steady light) was completely lost if even one background-noise light was flashing; and that steady signals were more effective (could be identified more quickly) than flashing signals if the proportion of the noise lights that were flashing was any greater than 1 out of 10. In other words, flashing lights against other flashing lights really make life difficult for the viewer.

TABLE C-2

SUMMARY OF VARIOUS VISUAL
CODING METHODS FROM (MCCORMICK, 1976)

Alphanumeric	Single numerals, 10*, single letters, 26, combinations, unlimited. Good, especially useful for identification, uses little space if there is good contrast. Certain items easily confused with each other.
Color (of surfaces)	Hues, 9 hue, saturation, and brightness combinations, 24 or more. Preferable limit 9. Particularly good for searching and counting tasks, poorer for identification tasks. Affected by some lights: problem with color-defective (color blind) individuals!
Color (of lights)	10, Preferable limit 3. Limited space required. Good for qualitative reading.
Geometric Shapes	15 or more. Preferable limit 5. Generally useful coding system, particularly in symbolic representation, good for CRT's. Shapes used together need to be discriminable, some sets of shapes more difficult to discriminate than others.
Angle of Inclination	24. Preferable limit 12. Generally satisfactory for special purposes such as indicating direction, angle, or position on round instruments like clocks. CRTs, etc.
Size of Forms (such as squares)	5 or 6. Preferable limit 3. Takes considerable space. Use only when specifically appropriate.
Visual Number	6. Preferable limit 4. Use only when specifically appropriate, such as to represent numbers of items. Takes considerable space, may be confused eith other symbols.
Brightness of Lights	3-4. Preferable limit 2. Use only when specifically appropriate. Weaker signals may be masked.
Flash Rate of Lights	Preferable limit 2. Limited applicability if receiver needs to differentiate flash rates. Flashing lights, however, have possible use in combination with controlled time intervals (as with lighthouse signals and naval communications) or to attract attention to specific areas.

*(Numbers refer to number of levels which can be discriminated on an absolute basis under optimum conditions.)

TABLE C-3

DESIRABLE CHARACTERISTICS OF AURAL WARNING SIGNALS (FROM DEATHERAGE, 1972)

o Use frequencies between 200 and 500 Hz, and preferably between 500 and 3000 Hz, because the ear is most sensitive to this middle range.

o Use frequencies below 1000 Hz when signals have to travel long distances (over 1000 ft), because high frequencies do not travel as far.

o Use frequencies below 500 Hz when signals have to "bend around" major obstacles or pass through partitions.

o Use a modulated signal (1 to 8 beeps per second or warbling sounds varying from 1 to 3 times per second), since it is different enough from normal sounds to demand attention.

o Use signals with frequencies different from those that dominate any background noise, to minimize masking.

o Preferably use high-intensity sudden-onset signals to alert receiver. Where earphones are used, consider dichotic presentation (alternating signal from one ear to the other).

o If different warning signals are used to represent different conditions, each should be discriminable from the others.

o Where feasible, use a separate communication system for warnings, such as loudspeakers, horns, or other devices not used for other purposes.

TABLE C-4

CHARACTERISTICS AND FEATURES OF AURAL WARNING DEVICES (FROM DEATHERAGE, 1972)

Alarm	Intensity	Frequency	Attention-Getting Ability	Noise-Penetration Ability
Horn	High	Low to High	Good	Good
Whistle	High	Low to High	Good if intermittent	Good if frequency is properly chosen.
Siren	High	Low to High	Very good if pitch rises and falls	Very good with rising and falling frequency.
Bell	Medium	Medium to High	Good	Good in low frequency noise.
Buzzer	Low to Medium	Low to Medium	Good	Fair if spectrum is suited to background noise.

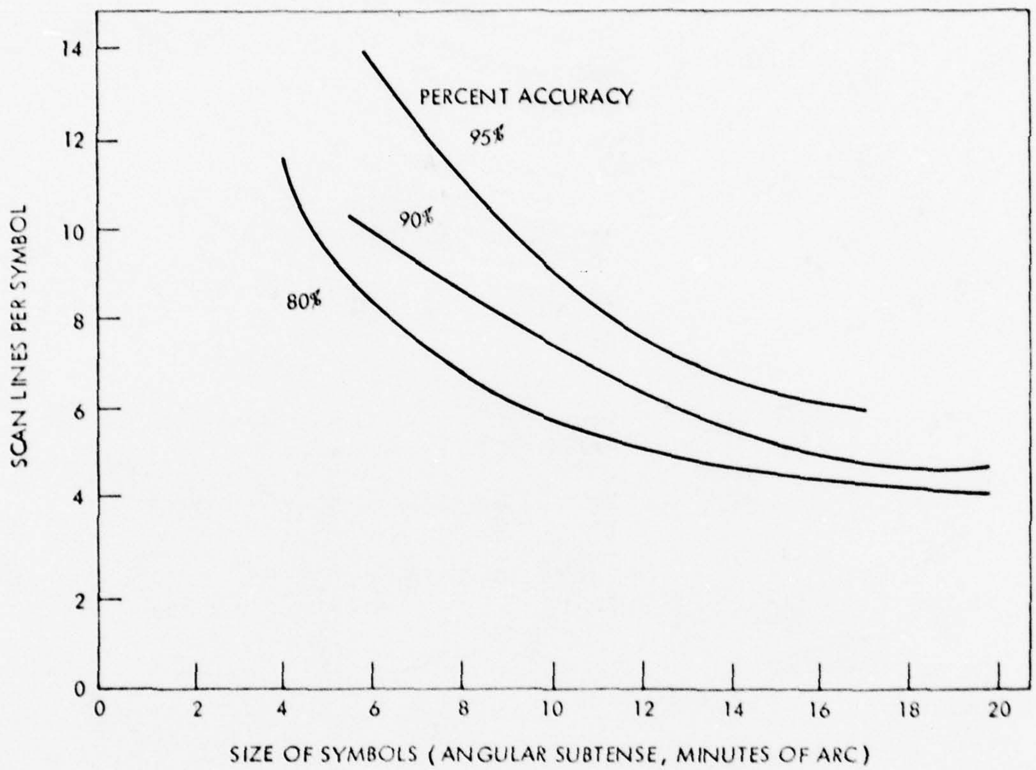


FIGURE C-1 - VARIATION OF IDENTIFICATION ACCURACY WITH NUMBER OF SCAN LINES AND SIZE OF ALPHANUMERIC AND GEOMETRIC SYMBOLS - FROM (HEMINGWAY AND ERICKSON , 1969)

APPENDIX D

EMPIRICAL METHODS FOR SHORT-TERM PREDICTIONS OF HAWSER LOADS

In this section empirical techniques for predicting maximum hawser loads based on recent measured values of hawser tension, wave height and wind speed are discussed. These prediction methods consist of two basic parts; the evaluation of statistical parameters which characterize the measured data, and the prediction of the expected maximum hawser tension using these parameters.

It is assumed that the following information is measured and available at all times:

1. Instantaneous wind direction and velocity.
2. Instantaneous wave height, period and direction.
3. Average current direction and speed.
4. Measured hawser tension.

In addition, it is assumed that a one hour forecast of wind speed and direction, significant wave height, wave period and wave direction are available (see Section 6.7 and Appendix F).

D.1 DETERMINATION OF STATISTICS OF MEASURED VALUES

The measured wind, wave and hawser tension data must be reduced to an easily interpreted form using only a small computing capability. The computing requirements depend on the frequency range of interest and the requirements of the hawser tension prediction procedures. The prediction procedures of Section D.2 require only the determination of the significant wave height and wave period, hawser tension, wind speed, and mean current speed. Straightforward averaging techniques will provide good estimates of the mean current speed; however, the

remaining values require further analysis.

Integrals of the energy spectra of the appropriate variables such as wind speed, wave height or hawser tension provide values for the significant heights and periods. However, computation of energy spectra requires the numerical evaluation of the Fourier transform of the autocorrelation function of the data. This calculation requires the storage of a sufficiently large number of samples to permit accurate evaluation of the autocorrelation function at low frequencies. In addition, an energy spectra may not be the most easily interpreted representation of the data. A straightforward tabulation of the peak values and periods occurring in a given time series is easier to compute and provides as much useful information.

A procedure similar to the one described below may be used to analyze wave, wind or hawser data. We assume $X(t_n)$ is the instantaneous value of data being analyzed. The mean $\overline{X}(t_n)$ can be calculated either by a continuous method

$$\overline{X}(t_n) = X(t_n)\ (1-r) + r\overline{X}(t_{n-1})$$

where $\overline{X}(t_{n-1})$ is the mean value at the previous time step and where r is a constant which governs how quickly the mean will respond to changes in the environment, or by a batch process

$$\overline{X}(t_n) = \frac{1}{N} \sum_{i=1}^{N} X(t_{n-i})$$

where N would determine how quickly the mean would respond to the environment. In both cases the lowest frequency with a significant amount of energy determines the minimum N or r.

Peak and trough values are defined as the maximum and minimum values between two up crossings of the instantaneous value past the mean value. The time between two up crossings

of the mean is the period. At each upcrossing of the mean value the period and height (|peak| + |trough|) is recorded. The range of heights can be stratified into discrete levels and the number of occurrences of a wave height and average period of each level recorded. In addition, the wave height squared is also accumulated for each level of period to provide wave energy distribution. After an appropriate number of mean up crossings the results can be stored and/or printed out and the process repeated. The total energy, standard deviation and average of the one-third highest values may be easily computed.

The time intervals between samples is a function of the shortest periods of interest. The number of samples over which data must be summed to obtain good estimates of statistical parameters is a function of the longest periods evident in the data. The length of time between samples should be about one to five seconds for surface waves and wind speed. The maximum wave period of interest is about 30 sec. The maximum wind gust period is about 150 sec. The latter implies that statistically valid variables can thus be determined every 10-15 minutes.

The hawser tension has several distinct frequency ranges. The lowest range (periods of 500-1200 secs) is associated with the unstable yaw motion of the tanker and has the largest amplitude. The pitch, heave and yawing motions induced by first order wave forces produce oscillations with periods 5-30 seconds. Dynamic effects such as hawser snapping and wave impacts on hawser cause oscillations at even higher frequencies. For our study, a sample time of 10-30 seconds would filter out the higher frequencies yet still describe the low frequency oscillation well.

Determination of the maximum and mean hawser tension

within an acceptable length of time requires special treatment of the data. Typically, there will be only three to five drift oscillations per hour. Since the environment changes significantly in an hour it is desirable to evaluate the mean and maximum hawser tensions in a similar time span. The small number of oscillations per hour requires that the beginning and length of summation periods must be carefully chosen to get reliable estimates of the mean. The tanker oscillation is approximately symmetrical so that there are two tension peaks per cycle. In changing environmental conditions one of these peaks will be consistently higher. The variation of maxima will be reduced if only the largest of the two peak forces per cycle is recorded.

The determination of the maximum hawser tension for each hour is not easily treated statistically. Examination of full scale hawser tension records shows that each cycle is not an independent event. Short of analyzing the transient behavior of the SPM in changing environmental conditions as described in Appendix E, a reliable estimate of the variation of the maximum hawser tension cannot be made with less than several hours of a steady-state environment. The time when a load prediction scheme is most needed, however, is when the environment is changing rapidly.

The problem of evaluating the mean hawser tension is considerably less difficult. An initial mean force may be obtained using available results as described in Section D-2. A new corrected mean hawser tension can then be estimated by summing the values for each cycle. A corrected mean force can be accurately determined every half hour using a summation of forces for the past hour or half hour. Thus, prediction of maximum hawser tension based on measured mean loads may be more consistent than

similar prediction based on measured maximum loads.

D.2 HAWSER LOAD PREDICTION TECHNIQUES

Based on the NSMB LOOP/Seadock model data (Remery and Wichers, 1975), the mean and maximum hawser loads can be related to a measure of the total environmental forces on the ship. An environmental force parameter, F_m, has been defined:

$$F_m = .02\, H_{\frac{1}{3}}^2\ \rho_w g B + .5\, V_m^2\ \rho_a A_T + .5 V_c^2\ \rho_w B T \qquad [D\text{-}1]$$

where:

A_T is longitudinal projected area of the above water hull,

$H_{\frac{1}{3}}$ is significant wave height,

ρ_w is water mass density,

g is gravitational acceleration

V_m is mean wind velocity,

V_c is current velocity,

ρ_a is air mass density,

B is ship beam, and

T is ship draft.

The expression for F_m is based on the assumption that the waves, wind and current come from the same general direction.

Figures D-1 and D-2 show data from the NSMB operational study (Remery and Wichers, 1975) plotted against F_m. The correlation between F_m and the mean hawser tension shown in Figure D-1 is good. A linear function of F_m will estimate all mean hawser tensions within 15 percent. The correlation for a particular set of wind, wave and current headings and a given ship is better in the full load condition than in the ballast condition. In the ballast condition the hawser loads for the

most severe environment fall 10-20 percent above the line defined by the less severe environments. Attempts were made to correlate this non-linearity with the magnitude of the tanker motion and the non-linearity in the hawser force displacement relation. Although some runs correlated well, the overall agreement was not good.

The maximum hawser tension also correlates with F_m but shows a larger scatter, as shown in Figure D-2. The relationship is more linear in the full load condition that when the ship is in the ballast condition. The absolute magnitude of the scatter is larger in the milder environments than it is in the more severe ones. This error is probably statistical in origin. The period of motion approaches the length of a test cycle for the larger tankers in the milder environments. Any maximum forces measured over one or perhaps two tanker oscillations will probably underestimate the actual maximum. A more sophisticated analysis relating the magnitudes of the tanker motion with the ratio of maximum to mean loads would be possible with a larger body of test data, and with data for longer duration tests.

D.3 PREDICTIONAL SCHEMES

There are a number of ways in which the processed environmental data described in Section D.1 and the general predictional approach described in Section D.2 can be combined into a usable predictional scheme. Four distinct methods have been selected for discussion. These are:

1. Prediction of peak load from predicted environment (wind speed, wave height and current speed) using a fixed empirical equation based on results such as shown in Figure D-2.

2. Prediction of peak load from predicted environment using empirical equations which are applicable only to the tanker size of interest (perhaps 5 separate equations would be used).

3. Prediction of peak load as in approach 2, except that the empirical equation would be modified or updated using data obtained during the earlier part of the mooring sequence.

4. Prediction of mean load as in approach 3, and use of an empirical relationship between mean and peak load applicable to the tanker size of interest.

These methods are briefly described below.

It should be noted that any empirical relationship such as shown in Figures D-1 and D-2, is applicable only to a general environmental configuration (relative headings of wind, waves and current). It is expected that load predictions will be of importance only for severe environments where wind and waves are likely to be nearly aligned. It is not certain that means will be provided for measuring wave direction, and observations of wave direction, particularly for confused seas, may be rather inaccurate.

The first approach, using an upper bound derived from a large body of measurements at a particular SPM, gives a quick and conservative estimate of hawser load relatively free from the problems associated with trying to measure enough maxima to insure statistical reliability. This procedure cannot, however, reflect the effect of differences in heading angles and ship parameters.

In the second approach one could use equation [D-1] or could start with an expression of the general form:

$$F_{max} = A + BH_{\frac{1}{3}}^2 + CV_w^2 + DV_c^2 \qquad [D-2]$$

The unknown constants, A, B, C and D, could be determined and stored for tankers of various size ranges which moored at the SPM.

In the third approach these coefficients would be updated after the tanker has been moored for several hours using some type of weighted least squares method. This procedure reflects the typical wind, wave and current heading angles occurring at the SPM, but, might be inaccurate for unusual combinations of headings.

Due to the difficulty in evaluating the maximum hawser load it may be better to use a fourth approach in which the mean load is determined using an equation of the same form as [D-2]. The maximum load would then be determined using a fixed relationship between mean and peak loads. The mean hawser force may be estimated fairly accurately in two or three cycles of motion by starting and stopping the integration at points of maximum load. At 1000 seconds per tanker oscillation the mean hawser tension could be reevaluated about every half hour.

The main difficulty with the last two approaches described is the difficulty of evaluating the mean and maximum hawser tension in a short enough time span. For short-term predictions, the change in the probable maximum hawser load in one-half to one hour is of interest. Since typical periods of motion are one-third to one-fifth of an hour, response determined for a one-hour period may contain long transients. In such cases, predictions based on steady state measurements may not be accurate.

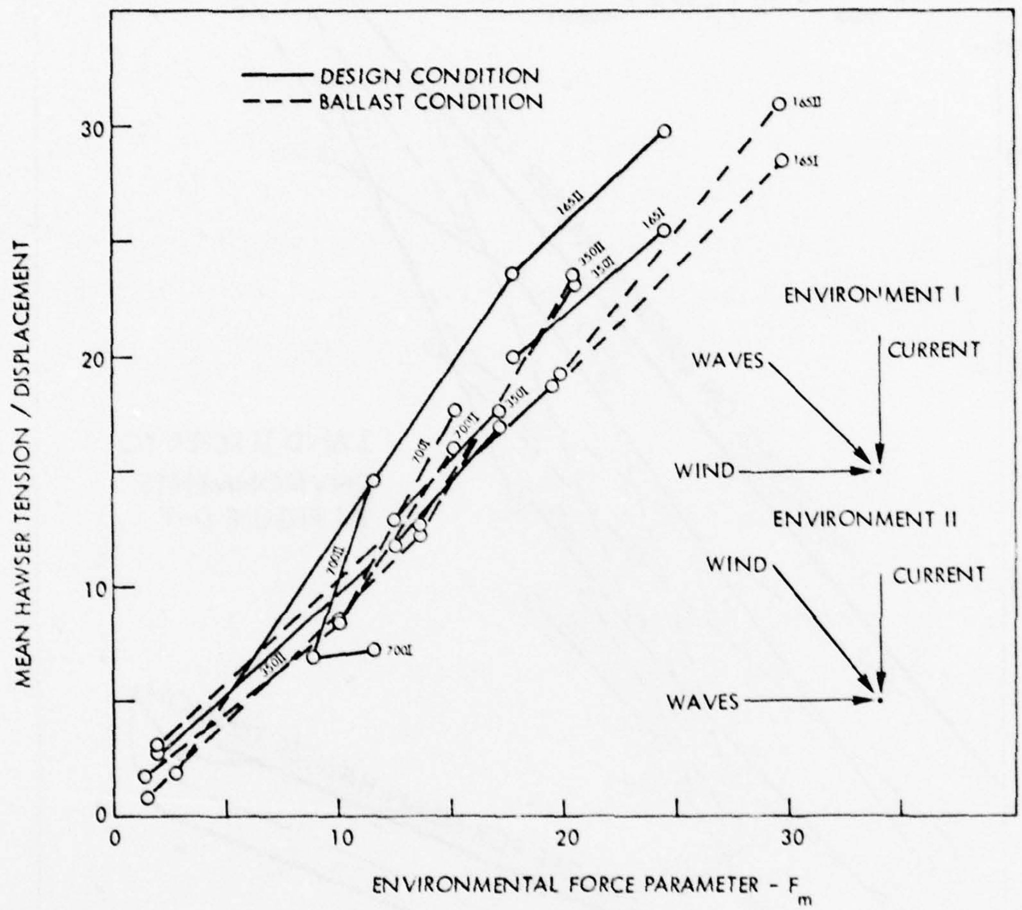


FIGURE D-1 - VARIATION OF MEAN HAWSER TENSION WITH ENVIRONMENTAL FORCE PARAMETER

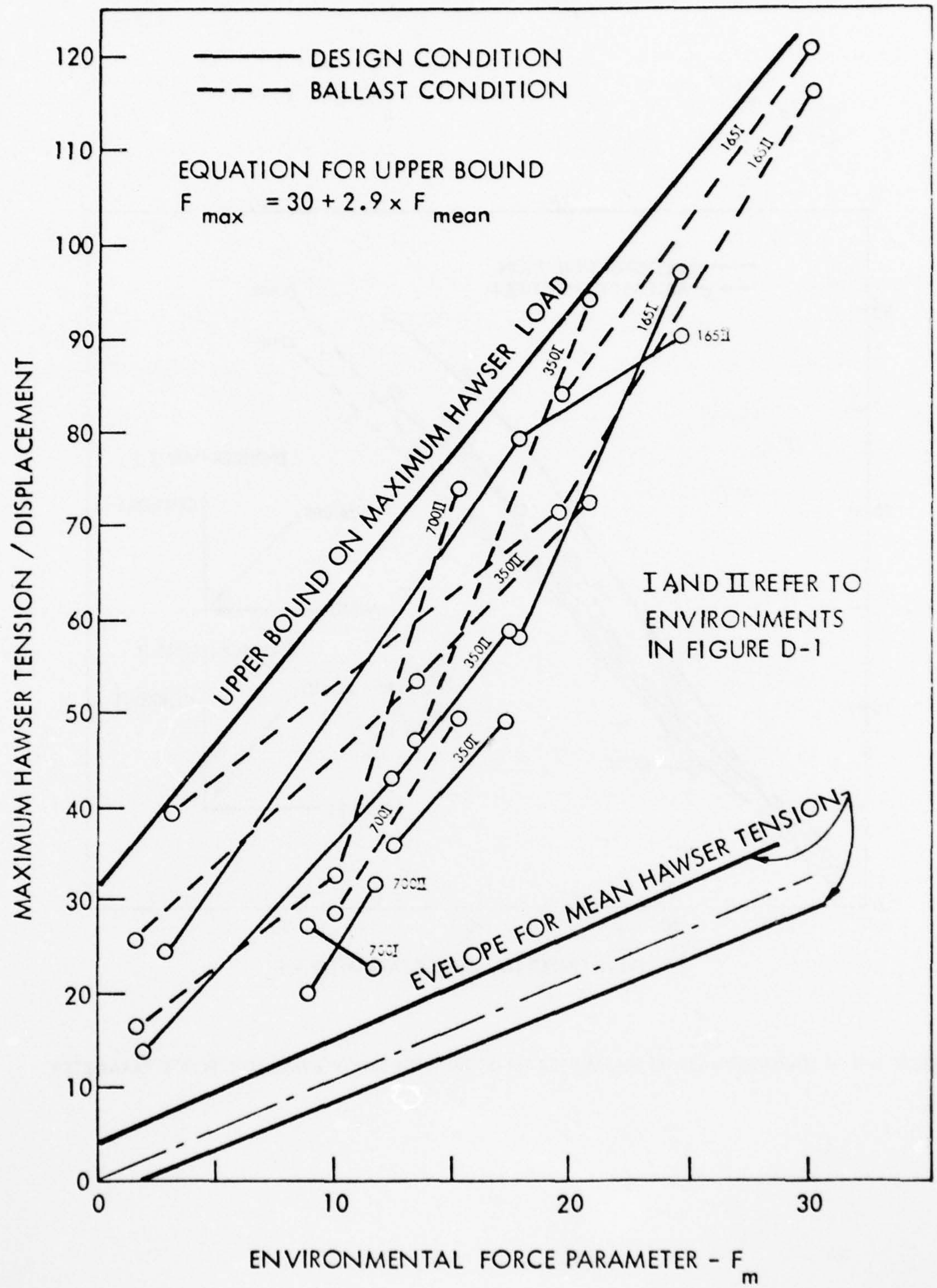


FIGURE D-2 - VARIATION OF MAXIMUM HAWSER TENSION WITH ENVIRONMENTAL FORCE PARAMETER

APPENDIX E

TIME-DOMAIN SIMULATION OF SPM BEHAVIOR

A single point mooring system consists of a buoy and its associated anchoring system, a hawser and the tanker. The final goal of the simulation described here is to predict the hawser loads for a given hawser, buoy, ship and environment. This capability combined with an environmental forecasting capability would provide a means of increasing the safety and efficiency of SPM operation. The intermediate goal for this simulation is to demonstrate that all of the principle characteristics influencing hawser loads are understood and can be modeled using acceptable computer time.

E.1 THEORETICAL APPROACH

The simulation models the SPM and tanker with five equilibrium equations, one for each of the allowed degrees of freedom. At each time step the forces on each element of the system are estimated and the resulting accelerations of ship and buoy are calculated. Numerical integration of the accelerations give the velocity and position of each element at the next time step. The process is repeated until a time history of suitable length is obtained.

E.1.1 Equations of Motion

The motions of the SPM system are described using the two coordinate systems shown in Figure E-1. The Oxyz system is fixed, with origin at the initial equilibrium location of the buoy. The Oxyz system coincides with the ship axes, with origin at the ship center of gravity. The equations describing the buoy surge and sway are written in the Oxyz coordinates.

The equations describing the ship surge, sway and yaw are

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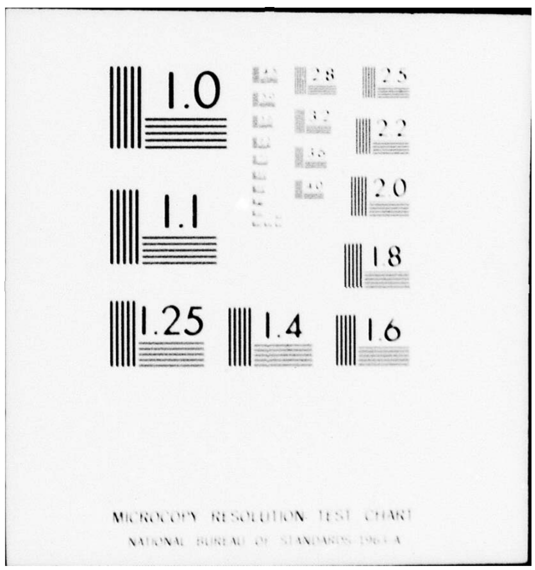
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written in the Oxyz coordinates. These equations are given below:

Buoy Surge

$$(M_b + M_b') \ddot{\bar{X}} = BX_{wv} + BX_h + B_u\bar{u} + BX_m$$

Buoy Sway

$$(M_b + M_b') \ddot{\bar{Y}} = BY_{wv} + BY_h + B_u\bar{v} + BY_m$$

Ship Surge

$$\begin{aligned} M_s (\dot{u} - vr) &= X_{wv} + X_{wd} + X_h \\ &+ \rho/2\ L^4\ [X_{rr}'\ r^2] \\ &+ \rho/2\ L^3\ [X_{\dot{u}}'\dot{u} + X_{vr}'vr] \\ &+ \rho/2\ L^2\ [X_{vv}'v^2 + X_{uu}'\ |u|u] \end{aligned}$$

Ship Sway

$$\begin{aligned} M_s (\dot{v} + ur) &= Y_{wv} + Y_{wd} + Y_h \\ &+ \rho/2\ L^4\ [Y_{\dot{r}}'\dot{r} + Y_{r|r|}'\ r|r|] \\ &+ \rho/2\ L^3\ [Y_{\dot{v}}'\ \dot{v}] \\ &+ \rho/2\ L^3\ [Y_r'ur + Y_{v|r|}'\ v|r|] \\ &+ \rho/2\ L^2\ [Y_*'u^2 + Y_v'uv + Y_{v|v|}'\ v|v|] \end{aligned}$$

Ship Yaw

$$\begin{aligned} I_z\ \dot{r} &= N_{wv} + N_{wd} + N_h \\ &+ \rho/2\ L^5\ [N_{\dot{r}}'\ \dot{r} + N_{r|r|}'\ r|r|] \\ &+ \rho/2\ L^4\ [N_{\dot{v}}'\ \dot{v}] \\ &+ \rho/2\ L^4\ [N_r'ur + N_{|v|r}'\ |v|r] \\ &+ \rho/2\ L^3\ [N_*'u^2 + N_v'uv + N_{v|v|}'\ v|v|] \\ &= N_t \end{aligned}$$

The coefficients in the maneuvering equations are defined as follows:

N_v $N_v' = \dfrac{N_v}{\frac{1}{2}\rho L^3 U}$ First order coefficient used in representing N as a function of v

$N_{\dot{v}}$ $N_{\dot{v}}' = \dfrac{N_{\dot{v}}}{\frac{1}{2}\rho L^4}$ Coefficient used in representing N as a function of $\dot{v}$

$N_{|v|r}$ $N_{|v|r}' = \dfrac{N_{|v|r}}{\frac{1}{2}\rho L^4}$ Coefficient used in representing N_r as a function of v

$N_{v|v|}$ $N_{v|v|}' = \dfrac{N_{v|v|}}{\frac{1}{2}\rho L^3}$ Second order coefficient used in representing N as a function of v

X_{wv} = X force due to waves

X_{wd} = X force due to wind

X_h = X force due to hawser

Y_{wv} = Y force due to waves

Y_{wd} = Y force due to wind

Y_h = Y force due to hawser

N_h = moment due to hawser

M_s = mass of ship

I_z = moment of inertia of ship about Z axis

L = length between perpendiculars

ρ = mass density of water

M_b = buoy mass

M_b' = buoy added mass

BX_{wv} = X force on buoy due to waves

BY_{wv} = Y force on buoy due to waves

BX_h = X force on buoy due to hawser

BY_h = Y force on buoy due to hawser

BX_m = X force on buoy due to mooring

BY_m = Y force on buoy due to mooring

$B_{\bar{u}}$ = damping coefficient

u = $\dot{x}$

v = $\dot{y}$

r = $\dot{\psi}$ = angular velocity of tanker

$\ddot{\bar{x}}$, $\ddot{\bar{y}}$ = acceleration of buoy in $\bar{x}$ and $\bar{y}$ directions

E.1.2 Hydrodynamic Forces on Tanker

The ship motion equations in the horizontal plane are based on the non-linear ship maneuvering equations (Goodman, et al. 1976). These equations were modified by omitting the propulsion and rudder terms and adding a resistance term $X_{uu}UU$ to the surge equation. The maneuvering coefficients experimentally determined by HYDRONAUTICS for the MARAD Series model H (Gertler, et al., 1974) were used for the computer simulation. The maneuvering coefficients were determined for several depth-draft ratios, so that shallow water effects were accounted for in the computer simulation.

The maneuvering equations are strictly valid only at the test Froude numbers and for motions which generate sway velocities which are small with respect to the forward velocities. To check the validity of these equations at low Froude numbers and large sway velocities, comparisons were made with experimental

measurements made on a different vessel at 1, 2, and 3 knots and all angles of attack. The results agreed qualitatively.

The surge maneuvering equation was modified to include an X_{uu} term which gives the resistance force in the X direction due to a motion in the X direction. The following procedure was adopted (Altmann, 1971):

$$X_{uu} \, |u|u = \tfrac{1}{2}\rho \, |u|u \, SC_R$$

$$C_R = C_r + C_F$$

$$C_F = \frac{0.456}{(\log_{10} R_e)^{2.58}} - \frac{1700}{R_e} \quad \text{Prandtl-Schlicting eq.}$$

This reference gives C_r values for tanker shapes which range from 0.0004 in the ballast condition to 0.0008 when fully loaded. A mean value of 0.0006 was used for calculations. No allowance for roughness or appendage drag was made.

E.1.3 Hydrodynamics and Mooring Forces on Buoy

The SALM 3-III and CALM buoys used in the NSMB Loop/Seadock tests (Remery and Wichers, 1975) were modeled for the computer simulation. The buoy properties are listed below.

	SALM 3-III	CALM	
Installed Displacement, tons	465	412	includes weight
Gross Displacement, tons (Displacement when completely immersed)	550	-	of water
Weight in Air, tons	203	337	in skirt
Height, ft	38	17.06	
Diameter, ft	24.5	39.37	
Anchor Chain, lbs/ft	-	433	
Non-dimensional Added Mass Coefficient (van Oortmerssen, 1971)	.81	.46	

The buoy viscous drag force was computed from

$$B_{\bar{u}} = .5\, \rho_w V^2 C_D hd$$

where

$B_{\bar{u}}$ = drag force,

h = buoy draft, and

d = buoy diameter.

The drag coefficient C_D was based on an empirical fit to data (van Oortmerssen, 1971):

$$C_D = .794 + .397\,(h/D)^3 + .0112\,(h/D)\,(h/d)^2 - .124\,(h/D)^2\,(h/d)$$

where D is the water depth.

E.1.4 Environmental Forces

The current, waves and wind combine to generate a complex set of forces which act on the SPM system. The forces generated by current are accounted for in the basic equations of motions described earlier. Wave and wind intensities vary in a random manner and therefore must be described statistically with an appropriate energy spectrum.

E.1.5 Wave Forces

Waves produce two types of forces; first order oscillatory forces at the wave frequency and second order, steady and low frequency drift forces. The first order forces are much larger in magnitude, but their high frequencies (typical periods are 5-15 seconds) make them relatively unimportant for the characteristic slow drift oscillations of a moored tanker. For such oscillations, steady and low frequency forces must be considered.

The computer simulation describes the statistical properties of ocean waves with the two parameter Bretschneider spectrum. For a significant wave height and mean apparent wave period, the energy content at a given frequency is

$$S_\zeta(\omega) = A\ \omega^{-5}\ e^{-B\omega^{-4}}$$

where

$k = (T_1/24.17)\ (4g/h_{\frac{1}{3}})^{\frac{1}{2}}$,

$A = .0081\ g^2\ k^{-4}$,

$B = 4A\ (h_{\frac{1}{3}})^{-2}$,

T_1 = mean apparent wave period,

$h_{\frac{1}{3}}$ = significant wave height,

ω = frequency, radians per second, and

g = gravitational acceleration.

When $k = 1$ this spectrum becomes the well-known Pierson-Moskowitz spectrum.

The mean wave drift force in an irregular sea may be expressed in terms of the wave spectrum and the drift force in regular waves (Pinkster, 1974):

$$F_m = L\rho g \int_0^\infty R^2(\omega)\ S_\zeta(\omega)\ d\omega$$

where the reflection coefficient $R(\omega)$ is given by:

$$R^2(\omega) \equiv F_d/[.5\ \rho g \zeta^2 L]$$

where

F_d = drift force in regular waves of frequency ω,

ρ = water mass density,

ζ = wave amplitude, and

L = LBP or beam.

$R(\omega)$ is a function of ship draft, water depth and hull shape. Measurements of $R(\omega)$ for a series 60 hull of 0.8 block coefficient in a water depth four times the vessel draft were used for this simulation (Remery and Van Oortmerssen, 1973).

The wave drift force produced by regular waves is steady. However, in an irregular seaway, wave groups will provide excitation at very low frequencies. The statistics of wave groups can be described by the energy spectra of the wave envelope. The envelope amplitude is one-half the distance between a line which connects the wave peaks and a line which connects the wave troughs as shown in Figure E-2.

It is assumed that the instantaneous drift force is proportional to the square of the wave envelope amplitude. It is shown (Nolte and Hsu 1972) that, in normalized form, the spectra for the envelope and the square of the envelope are equal and can be expressed as

$$E(\omega) = \frac{\int_0^{\infty} S_\zeta(\tau)\, S_\zeta(\tau+\omega)\, d\tau}{\int_0^{\infty} S_\zeta^{2}(x)\, dx}$$

A time history of the amplitude squared of the envelope can be approximated by a series of cosine functions as

$$E(t) = \sum_{k=1}^{N} [C_k \cos (t\omega_k + \varphi_k)]$$

where

$$C_k = \sqrt{E(\omega_k)\ (\omega_k - \omega_{k-1})},\ \text{and}$$

φ_k = random phase angle.

The instantaneous drift force may now be written as

$$F(t) = F_m \left\{ 1 + \sum_{k=1}^{N} [C_k \cos (t\omega_k + \varphi_k)] \right\}$$

The forces and moment due to waves at any heading to the ship are:

$$X_{wv} = .5\ \rho g B\ F(t) \cos (\psi_w)\ |\cos (\psi_w)|$$

$$Y_{wv} = .5\ \rho g\ LBP\ F(t) \sin (\psi_w)\ |\sin (\psi_w)|$$

$$N_{wv} = .5\ \rho g\ LBP\ F(t)\ (.01) \sin (2\psi_w)$$

where +.01LBP is the effective longitudinal center of the wave force (Wise and English, 1975) and ψ_w equals the angle between the ship heading and wave direction.

For the buoy, only mean wave forces were considered, as forces on the buoy are much smaller than forces on the ship. The mean force on the buoy is (van Oortmerssen, 1971):

$$F_b = .33\ d\rho g\ H_{\frac{1}{3}}^2\ R(\omega_1, d)$$

where

d = buoy diameter,

ω_1 = frequency corresponding to period T_1, and

$R(\omega_1, d)$ = analytically determined reflection coefficient.

E.1.6 Wind Forces

The forces and moments acting on the ship due to wind were calculated using the instantaneous wind velocity at the vertical location of the center of area. The wind velocity is assumed to consist of two components having the same direction, a mean velocity and a random, time varying velocity. The time varying velocity is assumed to be described by the Davenport Spectrum (Davenport, 1960). This spectrum is defined by

$$S(n)dn = \frac{4\kappa V_m^2 x}{(1+x^2)^{4/3}} dx$$

where

$S(n)$ = the energy per unit frequency $(Ft/sec)^2$,

dn = frequency increment in Hertz,

κ = surface drag coefficient,

V_m = mean wind velocity, and

x = a frequency parameter $4560n/V_m$ Hertz sec/ft.

A κ of .012 is assumed to be appropriate for wind blowing over waves. With this κ the RMS value of the steady wind is

$$V_{RMS} = \left[\int_0^\infty \dot{S}(n)dn\right]^{\frac{1}{2}} = \sqrt{6\kappa V_m^2} = .27\ V_m$$

The unsteady wind velocity is generated by dividing the energy spectrum into five bands of equal energy and representing each energy band by a velocity component having one-fifth the total energy. The magnitude of these sinusoidal velocity com-

ponents is:

$$V = \sqrt{6\kappa V_m^2/5} = .12\ V_m$$

The frequency of each component is chosen to give the same energy distribution as given by the Davenport spectrum. The maximum velocity will be $V_m + 5\ (.12\ V_m) = 1.6\ V_m$ which agrees well with various data given by Davenport. The instantaneous velocity is given by

$$V(t) = V_m \left[1 + .12 \sum_{n=1}^{5} \sin\ (w_n t + \varphi_n) \right]$$

where

w_n = frequency of nth component of wind, and

φ_n = random phase angle.

The component frequencies and periods for a 25 knot wind are:

n	x	ω^{-1} rad/sec	T = secs
1	0.61	0.04	157
2	1.38	0.09	70
3	2.65	0.17	37
4	6.00	0.39	16
5	31.6	2.04	3

These values were used for wind speeds from 15 to 45 knots.

The effective wind velocity, which includes the effect of the boundary layer at the water surface, was based on available empirical data (Altmann, 1971):

$$V_{we} = \left(\frac{z_{ca}}{32.81} \right)^{.15} \left[(u+V(t)\cos\beta_w)^2 + (V+V(t)\sin\beta_w)^2 \right]^{\frac{1}{2}}$$

where

z_{ca} = the vertical center of projected area of ship,

u = longitudinal ship velocity,

V = transverse ship velocity, and

β_w = angle between wind velocity vector and ship longitudinal axis.

The wind angle in the ship coordinates is:

$$\beta_{we} = \tan^{-1}\left(\frac{u + V(t)\cos\beta_w}{V + V(t)\sin\beta_w}\right)$$

Based on the sketches given in the NSMB Summary Report the following estimates were made for a 350 MDWT tanker:

	Design Draft	Ballasted Condition (.43T)
A_{px} sq.ft.	11,900	19,600
A_{py} sq.ft.	33,000	81,800
Z_{ca} ft	17.5	36.5
X_{ca} ft	-62.1	-25.2
A_R	0.35	0.45

Here

A_{px}, A_{py} = axial and lateral projections of area,

x_{ca} = longitudinal center of projected area,

Z_{ca} = vertical center of projected area, and

A_R = total shift in longitudinal center of pressure expressed as a percent of LBP, a function of aspect ratio.

Axial and lateral forces and yawing moment due to wind (from Altmann, 1971) are:

$$X_{wd} = \frac{1}{2} \rho_a C_x V_{we}^2 A_{px} \cos \beta_{we}$$

$$Y_{wd} = \frac{1}{2} \rho_a C_y V_{we}^2 A_{py} \sin \beta_{we}$$

$$N_{wd} = Y_w X_{LCP}$$

where C_x, C_y = axial and lateral drag coefficients.

$$X_{LCP} = x_{ca} + \frac{AR \cdot LBP}{\pi} \left(\frac{\pi}{2} - |\beta_{ew}| \right) \qquad -\pi < \beta_{ew} < \pi$$

The empirical formula for X_{LCP} and values of $C_x = .6$ and $C_y = .871$ were determined from wind tunnel tests (Altmann, 1971).

Wind forces on the buoys are small and were neglected.

E.1.7 Hawser Properties

Figure E-3 gives the simulated non-dimensional force displacement properties of a broken-in 2 in 1 type nylon hawser manufactured by British Ropes. This force displacement relation was used for both the computer simulation and the NSMB model tests.

E.1.8 Modeling of Buoy Mooring

The omnidirectional force displacement relation for a SALM buoy is derived from basic hydrostatics as:

$$H = xB / \sqrt{D^2 - x^2}$$

where

H = horizontal force

B = buoyancy of buoy

D = water depth

x = horizontal displacement of buoy.

The force displacement relationship for a CALM buoy depends on the number, pretension and orientation of the catenary anchor legs. The CALM buoy was assumed to have six anchor legs arranged symmetrically. The force displacement relation for each anchor leg is, from the equations of a catenary:

$$\frac{x}{D} = 1 + \frac{H}{wD} \ln \frac{1 + H/(wD) - \quad 1 + 2H/(wD)}{H/(wD)} - ((1 + 2H/(wD)))^{\frac{1}{2}}$$

where w is the submerged weight per foot of the anchor chain and x is the horizontal displacement of the given leg. The initial displacement is determined by the pretension.

E.2 NUMERICAL CONSIDERATIONS

The system of equations governing the buoy and tanker motions is "stiff." A "stiff" set of equations contains two natural frequencies which are widely separated. In this case the natural frequency of the moored buoy is much higher than that of the tanker. Numerical stability requires that the integration time step be less than one fifth the smallest natural period in the system. However, satisfying this requirement results in a time step which is far too small for efficient calculations of tanker motions. The program efficiency can be improved by using a short time step for solving the buoy equations and then solving the tanker equations only after each n integrations of the buoy equations. Appropriate values of n for these cases were 10 to 20.

Using this procedure, twenty seconds of SPM simulation requires one to two seconds of computer time on the HYDRONAUTICS 1130/META 4 Computer. The resulting computer cost is approximately five dollars per hour of simulation. The cost would be

somewhat less on a large commercial computer. Long term predictions are therefore feasible with computers comparable in speed to the 1130/META 4. The computational efficiency of the program used here is not optimum.

E.3 RESULTS OF COMPUTER SIMULATIONS

Table E-1 reviews all of the computer simulations. Table E-2 compares results obtained from computer simulations with corresponding model data from the NSMB Loop/Seadock model tests. Table E-3 presents results from computer simulations evaluating the stability of the moored ship under the individual influence of wind, waves and current. Finally, the results of a systematic variation of wave and wind heading angles is presented in Table E-4.

After the initial transient motions, the simulated tanker oscillates about an equilibrium position. The maximum, minimum and mean values of the hawser load, bow position and ship heading angle for steady state oscillations, as tabulated are sufficient to describe the SPM response. The periods of tanker oscillatory motion are approximately 1000 seconds for the ballast condition to 1600 seconds for the full load condition.

Before discussing the general SPM behavior, it is useful to examine SPM response to steady forces in the environment. Runs 1-5 examine the SPM response to the individual influence of wind, waves, and current. For these runs, the mean value of the time dependent force is used. In each case, a small disturbance from the equilibrium position will cause an oscillating motion which will grow until a steady amplitude and period is reached. If the magnitude of the applied force is increased the steady state period decreases but the amplitude does not change significantly.

Such instability depends on the physical configuration of the buoy, hawser and tanker. Abkowitz (Abkowitz, 1976) discusses instability in current and gives a stability criteria in which stability decreases with increasing hawser length. The restoring moment provided by the hawser is proportional to the hawser tension and inversely proportional to its length. The disturbing moment developed by the ship is proportional to the side force and its longitudinal center of application. Therefore, reducing the ratio of C_{wx}/C_{wy} or moving the ship longitudinal center of area (LCA) forward will reduce the stability in wind and reducing the beam to length ratio will reduce the stability in waves. Combining more than one environmental influence with different headings tends to stabilize the SPM response. When the vessel is stable, it will move to an equilibrium position and become stationary.

The complete response of the SPM may be viewed as the non-linear combination of responses due to the steady and time dependent components in the environment. If the SPM is stable, the time dependent forces cause the tanker to oscillate with a regular period and amplitude and an equilibrium position determined by the mean environmental forces. When the SPM is unstable, the mean environmental forces will produce large oscillatory motions. The effect of the time dependent environmental forces on the unstable motions is not clear.

Computed results agree best with experiments when the enviromental forces and the resulting motions are large. Run 6, a ballast condition in which the tanker is unstable, produced mean hawser loads and motions which are approximately 75 percent of the measured values. For the full load condition in the same environment, runs 7-11, computed mean loads and motions are about 60 percent of measured values. The worst agreement occurred with the least severe environment, runs 14, 15 and 16. In these runs

maximum excursions of the bow are less than two percent of the ship length and the change in heading less than 10 degrees.

For the small motions observed in runs 14-16, a linear system using the local rate of change of force with heading for each environmental force could be used to analyze the system response. Such a system would be linear. Therefore, the hawser loads would have a linear relationship with the applied forces which in turn are proportional to the energy contained in the environment. This may explain the observed correlation between the environmental energy and hawser loads as described elsewhere in this report.

The ship equilibrium position depends on the relative current, wave and wind forces. As a result, it is sensitive to errors or changes in any of the environmental forces. Examination of runs 6-11 indicates that the computed equilibrium position is closer to the fixed $\bar{x}$ axis than is the measured position. This implies that the mean wave force is underestimated relative to current induced forces. It has been shown (Muga and Fong, 1976) that the reflection coefficient for water depth to draft ratio of two is approximately twice that for deep water. In run 13 all wave forces were increased by a factor of two. The computer equilibrium position and mean hawser force are closer to the measured value, but the ratio of maximum to mean hawser force is not improved.

The measured ratio of maximum hawser load to mean hawser load is consistently greater than the computed ratio. The measured ratio ranges from 5.73 to 2.48 where the computed ratios were from 3.07 to 1.04. Agreement for maximum loads was best for cases with the best agreement for ship motions. There is

clearly a correlation between agreement of maximum loads and motions.

In the NSMB tests environmental conditions typical for the proposed port location were used. Other combinations of wind wave and current headings may produce larger hawser loads. Runs 17-20 show that the hawser loads decrease uniformly as the angles between the wind, waves and current increases. The hawser loads are 30 percent larger when all of the environmental disturbances have the same heading than when the headings from the NSMB tests were used. Separating the headings inhibits the unstable tanker oscillations.

The measured tanker oscillations have a shorter period than the simulated oscillations. This difference is probably due to shallow water effects. The hydrodynamic coefficients used in the simulation were determined at a forward speed of eight knots. Added mass in shallow water is speed dependent, and using a shallow water coefficient for eight knots will result in over estimating the shallow water added mass at two knots. Run 12 in which deep water maneuvering coefficients were used shows a shorter period, larger motions and a larger maximum hawser load to mean hawser load ratio than in run 7, the corresponding run using the shallow water coefficients.

E.4 CONCLUSIONS

The computer simulations exhibit the same types of motions under the same environmental conditions as do the NSMB experimental results; however, the predicted mean and maximum hawser loads are consistently low. These differences may be due to the approximations used for the environmental loads. Better estimates for the wind loads and hydrodynamic loads can be obtained by using standard experimental techniques. Wave drift

forces and moments are still not well understood and systematic data on the effects of depth, heading angle and irregular wave trains are not available. Description of the low frequency components of the wave drift and wind drag forces are particularly important in determining the amplitude of motion. A better means for estimating these forces is essential for good quantitative predictions of moored ship behavior and hawser loads.

TABLE E-1

SUMMARY OF COMPUTER SIMULATIONS

Run	Condition	H_s, Ft	Tm Sec	ψ^o Wave	Wind Speed Ft/sec	ψ^o Wind	C_{wx}	C_{wy}	LCA	Current Knots	Notes
1	Full Load	-	-	-	-	-	-	-	-	2.0	
2					59.0	0	0.6	0.815	-62.1	0	
3					59.0	0	0.6	0.815	-30.0	0	
4					59.0	0	0.4	1.0	-3.0	0	
5	Full Load	13.2	8.0	0	-	-	-	-	-	-	
6	Ballast	15.0	11.5	-90	76.0	-45	0.8	0.871	-25.2	1.0	NSMB 2102
7	Full Load	15.0	11.5	-90	76.0	-45	0.4	0.871	-62.1	1.0	NSMB 2040
8							0.6		-62.1		
9							0.8		-62.1		
10							0.6		-30.0		
11							0.6		0.0		
12							0.6	0.871	-62.1	1.0	Deep Water Maneuvering Coeffs.
13	Full Load	15.0	11.5	-90	76.0	-45	0.6	0.871	-62.1	1.0	Shallow Water Wave Effects
14	Full Load	15.0	12.0	-90	76.0	-45	0.6	0.871	-62.1	1.0	NSMB 2467
15		12.0	10.1	-45	59.0	-90				1.0	NSMB 2475
16		4.0	7.4	-45	16.9	-90				0.5	NSMB 2478
17	Ballast	15.0	11.5	0	76.0	0	0.6	0.871	-25.2	1.0	
18				-15		-30					
19				-30		-60					
20	Ballast	15.0	11.5	-45	76.0	-90	0.6	0.871	-25.2	1.0	

TABLE E-2

COMPARISON OF COMPUTER SIMULATION RESULTS WITH NSMB DATA

Run	Hawser Load Tons Mean	Min	Max	$\overline{X}_{Bow}$ Ft Mean	Min	Max	$\overline{Y}_{Bow}$ Ft Mean	Min	Max	ϕ Degrees Mean	Min	Max	Hawser Tension Max/Mean
6	72.3	20.1	222.3	-115	-264	+31	170	-54	+275	-43.7	-60.7	-17.2	3.07
NSMB 2102	95.5	0	509.2	-153	-322	+82	+223	-21	+309	-56.3	-76.5	-35.8	5.33
7	32.7	30.0	35.7	-245	-247	-241	+22	-9	+52	-44.7	-45.8	-43.6	1.09
8	36.9	33.1	42.9	-244	-248	-238	+47	+21	+75	-44.7	-45.8	-43.6	1.16
9	43.3	38.8	49.1	-241	-247	-235	+72	+47	+92	-45.0	-46.4	-43.6	1.13
10	37.6	33.2	42.7	-244	-248	-237	+47	+21	+76	-45.0	-46.4	-43.5	1.14
11	36.9	33.5	42.8	-244	-248	-237	+47	+20	+76	-45.0	-46.4	-43.5	1.16
12	39.6	27.5	52.7	-165	-200	-125	+179	+144	+214	-51.9	-47.9	-46.4	1.33
13	54.37	44.64	62.5	-213	-229	-199	+137	+114	+163	-53.3	-54.4	-51.7	1.15
NSMB 2090	59.2	5.6	147.0	-224	-273	-217	+180	+138	+222	-54.1	-57.1	-51.4	2.48
14	35.2	32.9	37.2	-211	-212	-211	+27	+25	+30	-44.1	-44.6	-43.6	1.06
NSMB 2467	61.9	0	171.9	-185	-209	-158	+168	+142	214	-53.0	-56.5	-49.7	2.78
15	35.2	33.8	36.5	-214	-215	-214	-9	-10	-9	-32.0	-32.0	-32.0	1.07
NSMB 2475	41.0	0	150.8	-240	-249	-231	+15	-33	+45	-44.0	-49.3	-40.7	3.68
16	6.3	6.2	6.8	-188	-188	-187	-66	-67	-66	-24.9	-25.2	-24.6	1.08
NSMB 2478	8.6	0.8	49.3	-223	-227	-219	+13	-12	+35	-16.8	-19.2	-14.4	5.73

TABLE E-3

EFFECT OF WIND AND WAVE HEADING

	Hawser Tension Tons			$\overline{X}_{Bow}$ Ft			$\overline{Y}_{Bow}$ Ft			ψ Degrees		
Run	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
17	89.2	20.2	269.6	-225	-326	-123	+0	-241	+244	-1.0	-27.0	+27.0
18	89.1	23.17	266.1	-206.4	-320	-65	52.4	-195	+266	-13.5	-38.4	-13.2
19	75.95	20.7	210.3	-171	-301	-12	+103.6	-138	+276	-23.8	-49.9	0
20	68.9	20.8	212.1	-166	-266	+29	+152	-47	+274	-40.1	-60.7	-17.8

TABLE E-4

STABILITY UNDER THE INDIVIDUAL INFLUENCES OF WIND, WAVE, AND CURRENT

	Hawser Tension Tons			$\overline{X}_{Bow}$ ft			$\overline{Y}_{Bow}$ ft			ψ Degrees		
Run	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1	17	0	45	+11.8	-176	+140	+19	-185	+167	+0.01	-11	+10
2	12	6	16	807	800	814	0	-50	+50	0	-6	+5
3	8	6	16	-197	-193	200	0	-54	+56	0	-5	+5
4	12	0	30	-157	-204	-120	-4	-159	+140	-1	-15	+20
5	23	0	29	-208			+1	-5	+7	-0	-0	+9.5

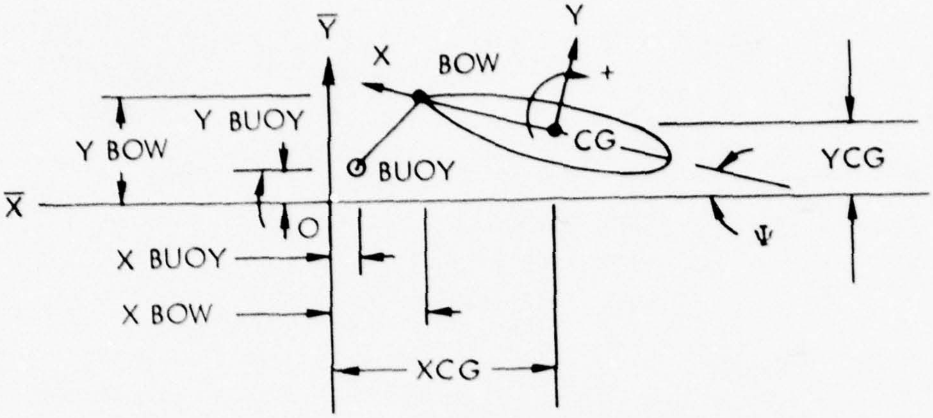

FIGURE E-1 - DEFINITION OF COORDINATE SYSTEMS

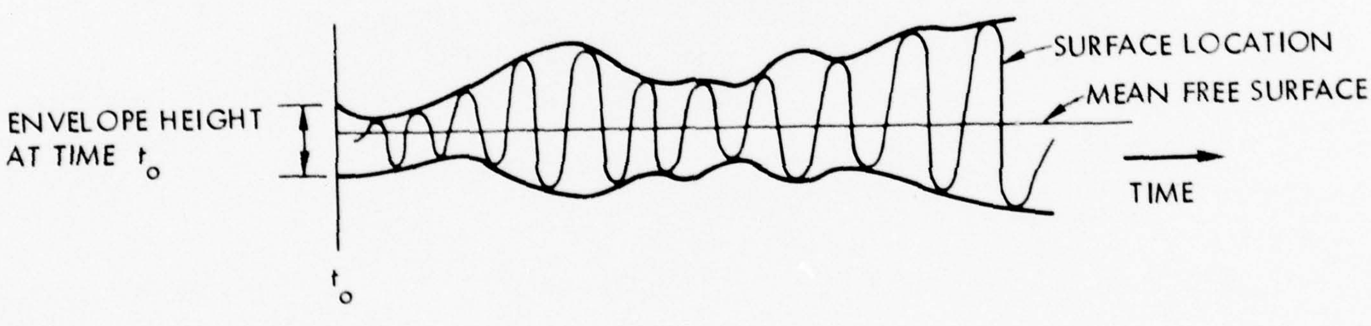

FIGURE E-2 - VARIATION OF WAVE ENVELOPE HEIGHT WITH TIME

APPENDIX F

METHODS FOR PREDICTING WAVE HEIGHTS AND CURRENT

It is not feasible within the scope of this study to consider, in detail, the many available methods for predicting wave heights and current. In general, it is not possible to recommend the methods most suitable for use in a MLPS, although some methods which may be appropriate are discussed in this Appendix.

It appears very likely that a U. S. DWP will rely on the services of a company providing continuous wind and wave predictions. Such a service and the prediction methods used by the service are described in a recent OTC paper (Silveria and Skees, 1978). Twelve hour wave predictions have been shown to be in good agreement with measured wave records (Silveria and Skees, 1978).

F.1 PREDICTION OF WAVE HEIGHTS

A wave height predictional method selected for use in a MLPS should be suitable for use in a relatively simple computer program. It must be capable of predicting wave heights for relatively shallow water (say 100 feet water depth) and should, ideally, be capable of accounting for spatial and temporal variations of wind velocity. Published methods do not appear to meet these requirements. Available prediction methods are most highly developed and most adequately validated for deep water waves. Methods for predicting waves in shallow water or water of decreasing depth (such as on the Continental Shelf where U. S. DWP's are likely to be located) are less satisfactory.

Predicted wave heights are generally of interest for DWPs only during periods of increasing wave height, and hence decaying wave conditions are not of interest. Maximum hawser loads

will generally result (at least for the Gulf of Mexico) from squalls of short duration and limited area. All DWP operations will be shut down well before the onset of hurricanes or other large storms. A wave prediction method selected for use at a DWP should, therefore, be suitable for treating waves resulting from squalls, or other short-term phenomena.

F.2 PREDICTION OF WAVE HEIGHTS IN DEEP WATER

There are three well-developed methods for wave forecasting or predicting (Bretschneider, 1967-68). These are the significant wave or SMB method, the space-time field or STF method and the wave spectrum or PNJ method. The advantages and disadvantages of these methods are well defined in (Bretschneider, 1967-68). The primary advantage of the SMB method is its extensive validation with field data and its applicability to shallow water. Another method which may be useful was developed by Inoue (Inoue, 1966).

The latest SMB method, which is based on a set of equations first given by Wilson (Wilson, 1954), is based on the following equations (Bretschneider, 1977):

$$\frac{gH_s}{U^2} = A \tanh \left[B \left(\frac{gF}{U^2} \right)^m \right]$$

$$t_{min} = 2 \int_0^{F_{min}} \frac{1}{C_o}\, dx$$

$$\frac{T_{max}}{\frac{U}{(1.689)}} = 0.4 \tanh \left\{ \ell n \left(\left[\frac{1 + \frac{40\,H_s}{U^2}}{1 - \frac{40\,H_s}{U^2}} \right]^{\frac{1}{2}} \right) \right\}^{0.6}$$

where $A = 0.283$

$B = 0.0125$

$m = 0.42$

C_o is the phase velocity of the wave

H_s is significant wave height, feet

T_{max} is wave period for maximum energy, seconds

F is fetch length, feet

U is average wind speed at 10 meters above water surface, feet/second

t is duration of time

These equations have been solved graphically. The results are reproduced in Figures F-1 and F-2. The periods shown in the figures are somewhat incorrect. This method or figure can be used to predict wave heights with changing wind speed (Bretschneider, 1967-68). However, the method was developed for constant wind direction, and probably cannot be used when significant changes in wind direction occur. It is assumed that the predominant wave direction is the same as the wind direction.

The SMB method and the other methods referenced above are not ideally suited for DWP use because they generally involve numerical integration or graphical solution, but they can certainly be used as the basis for a method appropriate to DWP use.

F.3 PREDICTION OF WAVE HEIGHTS ON THE CONTINENTAL SHELF

There do not appear to be any wholly satisfactory methods for predicting wave heights on the Continental Shelf. Many available methods for treating shallow water waves (Bretschneider, 1972) are not applicable to the water depths and changes in depth associated with probable DWP locations on the Continental Shelf.

A recent method for predicting wave spectra in shallow water and particularly for predicting the change in wave energy spectra as waves move from deep to shallow water is given by Collins (Collins, 1972). This method requires numerical integration of a partial differential equation describing the change of wave energy spectrum with wave depth, distance along the wave path, wave frequency and wave group velocity. This approach may be too cumbersome for use in DWP MLPS. It should be feasible, however, to use it to precalculate appropriate corrections for representative deep water spectra predicted by methods such as described in Section F.2.

F.4 PREDICTION OF CURRENTS

Currents are generally assumed to be composed of three components:

1. Geostrophic - due to large-scale movements of oceanic waters.
2. Tidal.
3. Wind-driven or Eckman current due to shear forces at the air-water interface.

The geostrophic and tidal currents are generally known or can be determined for a given location. Geostrophic currents vary seasonally while tidal currents vary on an approximate 12-hour cycle. For proposed U. S. DWP locations (Gulf of Mexico) geostrophic and tidal currents will probably be small enough to neglect in predicting mooring loads, but this should be confirmed using available data or data acquired at the DWP site.

Wind-driven currents can be significant for strong longshore winds (winds parallel to the coast). The prediction of surface currents in the Continental Shelf with parallel depth contours is considered by Bretschneider (Bretschneider, 1967-68,

Part 1). The rates of longshore current speed to wind speed is given by:

$$\frac{V_c}{V_w} = D^{1/6} \sqrt{\frac{k}{K} \sin a} \tanh \left\{ \frac{V_w t}{D} \sqrt{\frac{k\ K \sin a}{D^{1/3}}} \right\}$$

where
V_c is current speed in feet per second
U is wind speed in feet per second
k is surface wind stress parameter
K is bottom sea bed stress parameter
t is duration of wind speed in seconds
a is the angle of the wind measured from a perpendicular to the coast line
D is water depth in feet

Bretschneider recommends the use of values of k and K of 3×10^{-6} and 0.01, respectively. For cases where the wind blows toward the coastline, there will also be a component of surface current velocity normal to the coast and in the direction of the wind. Suitable methods for predicting this normal component do not appear to exist (Bretschneider, 1967-1968, Part 1).

Figure F-3 shows steady-state, nondimensional current speed. Steady-state current speed will generally occur after two to ten hours.

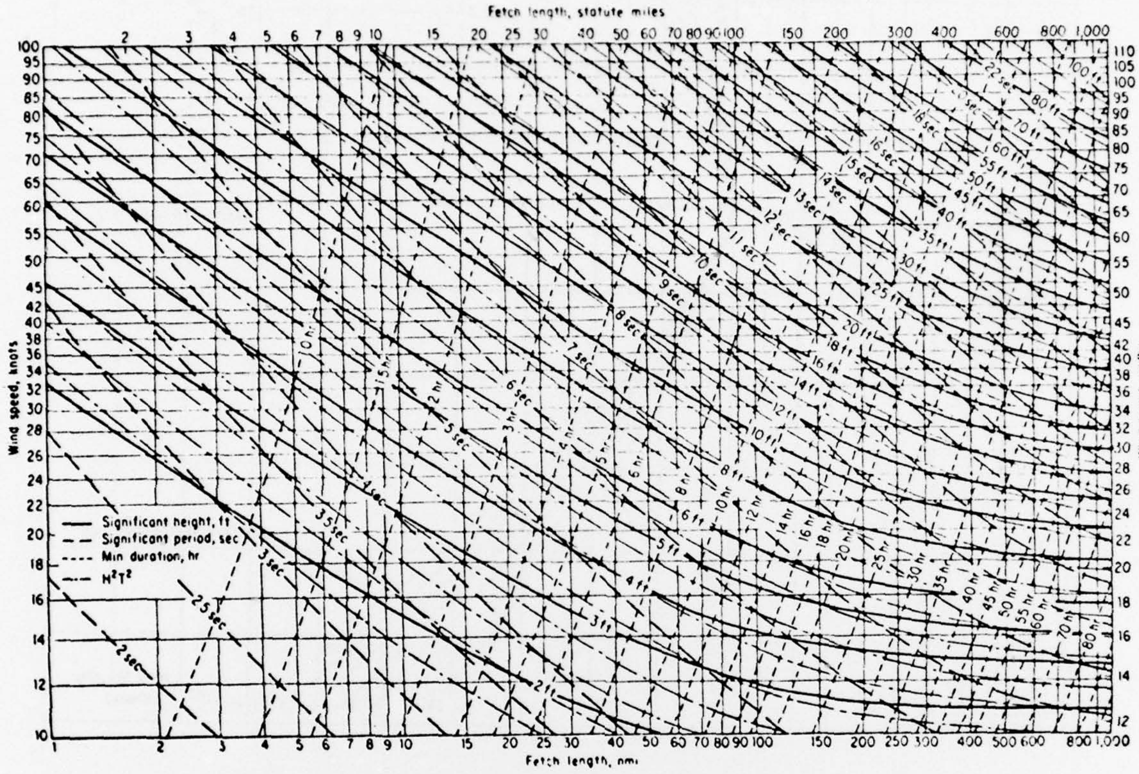

FIGURE F-1 - DEEP-WATER-WAVE-FORECASTING CURVES AS A FUNCTION OF WIND SPEED, FETCH LENGTH, AND WIND DURATION (FOR FETCHES 1 TO 1,000 NM) (FROM BRETSCHNEIDER, 1967-68)

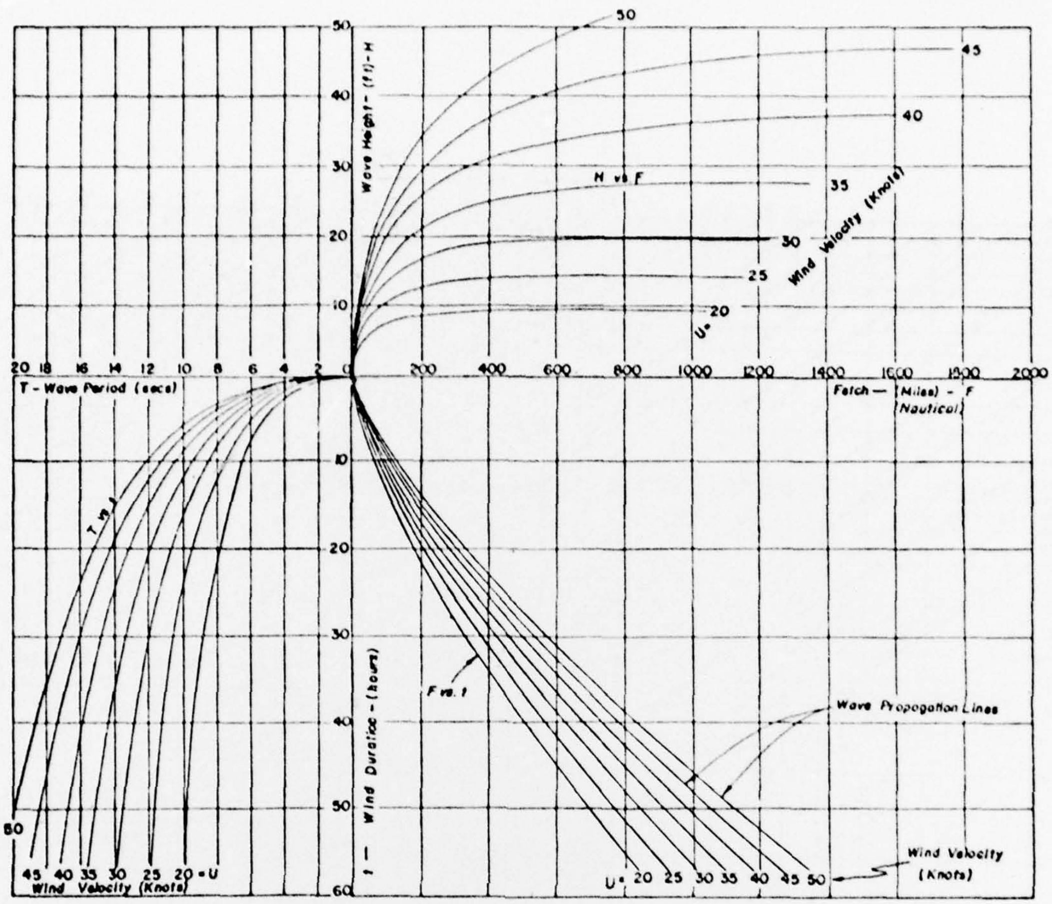

FIGURE F-2 - DIAGRAM FOR FORECASTING WIND-GENERATED WAVES
(FROM WILSON, 1954)

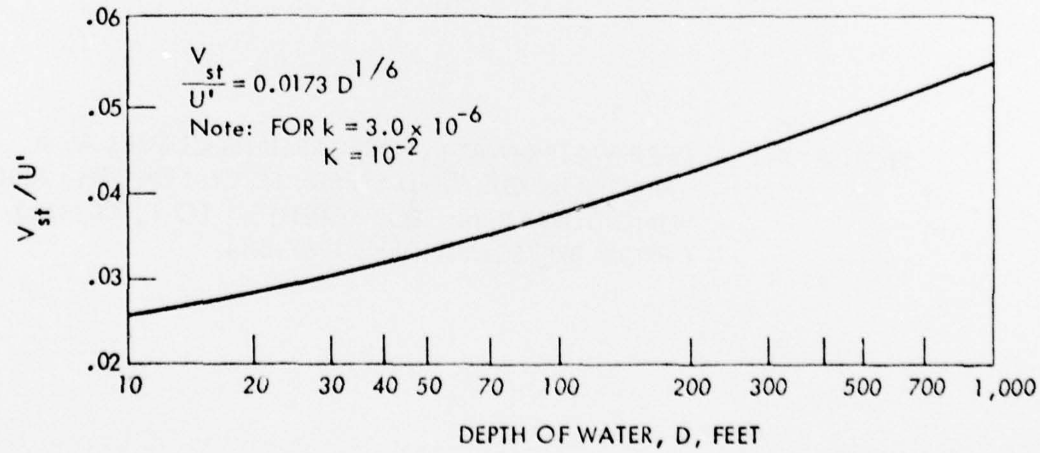

FIGURE F-3 - STEADY -STATE CURRENT SPEED AS A FUNCTION OF WATER DEPTH

APPENDIX G

BRIEF REVIEW OF POSSIBLE LNG DEEPWATER PORTS

There is currently considerable interest in California in LNG import terminals. Several studies of such terminals have been sponsored by Western LNG Terminal Associates. The most recent was a comprehensive study of various candidate terminal concepts by Fairchild Stratos (Tatge, et al., 1977). Currently, the State of California is sponsoring studies of such terminals. This interest derives from the potentially greater safety of offshore rather than onshore terminals.

In the Fairchild study (Tatge, et al., 1977) five terminal concepts were considered: natural island, artificial islands, floating facilities, fixed and mobile structures and subsea structures. It was concluded that all concepts were technically feasible. Western LNG Terminal Associates (WLNGTA, 1977), in comments on this report, concluded that either a floating or a subsea facility would probably be required. These concepts have problems, however, including liquid transfer from ship to receiving terminal and the design and testing of the rotary gas joints and the mooring system for the floating structure.

Table G-1, from the Fairchild study, shows characteristics of various proposed terminal concepts. Nine of the 14 concepts are floating facilities or structures. The floating structures are generally one or more barges.

The floating structures will generally require two moorings, the barge mooring and the ship-barge mooring. Typically, it is proposed that the ship be moored alongside the barge, although this type of mooring permits operation in less severe wind and wave conditions than those with a SPM. In a number of proposed

floating concepts, Table G-1, the barge or barges are moored using SPMs. In the subsea concepts the above water portion of the structure is generally tower-like and the ship is moored with a SPM.

It seems likely that if LNG import DWPs are built they will probably incorporate one or more moorings and that mooring load monitoring systems will be essential features of these DWPs. The requirements for these mooring systems are likely to be different than those for an oil SPM, however.

TABLE G1 - PROPOSED LNG TERMINAL CONCEPTS FROM (TATGE, ET AL, 1977)

PROPOSER	TECHNIGAZ	BROWN & ROOT	GLOBAL MARINE	INTERNATIONAL PROCESS INDUSTRIES	ISHIKAWAJIMA HARIMA HEAVY INDUSTRIES COMPANY (IHI)	KVAERNER MOSS	THYSSEN NORDSEEWERKE
CATEGORY	Floating	Floating	Floating	Floating	Floating	Floating	Floating
DESCRIPTION OF SUBSYSTEM	Two or more barges fixed together with SBM mooring in 450 foot water depth	Two storage barges plus a machinery platform. 80 to 100 foot water depth preferred	Floating concrete barge (168,000 m^3 storage capacity) with mooring tower (150 foot water depth)	Two barges with storage and process on each connected by pipeline through SBM	Single steel barge with storage and process in 80 meters of water. Excerpts from proposal to Japanese company	Three barge like sections joined at the site and moored by a SALS. Based on data from proposal for a liquefaction facility	Two modules, joined at the site, with single point mooring. Concept based on LPG (non-cryogenic) systems.
RELATED EXPERIENCE AND EQUIP. IN OPER.	LNG carriers and land based tanks, LPG and NH_3 receiving terminals	Extensive offshore drilling and production experience world wide, also, subsea pipeline	GMDI and the parent GMI experienced in design and construction supervision of drill and deep ocean mining vessels	IPI has no experience in offshore process plants to date. Site general knowledge and team association	Extensive experience in LNG receiving terminal design and construction plus a good background in marine LNG application	Moss has extensive experience in design and construction of LNG carriers and other ships, also detailed engineering on a floating liquefaction facility	Extensive experience in design and construction of LPG carriers and other types of ships.
PROPOSAL DESIGN STAGE	Very preliminary, no details presented	Very preliminary, no details presented	Quite well advanced model test and stress analysis complete for similar facility	Very preliminary concept. Few details presented.	Proposal stage for a similar project; no work accomplished for baseline requirements	Very preliminary stage, all data extracted from liquefaction facility work	Preliminary stage; no work with cryogenic systems indicated.
DEVELOPMENT TO DATE ON CONCEPT	None indicated	None indicated	Model testing and engineering analyses	None indicated, will rely on expertise of team	None indicated	None indicated on receiving terminal but model test on liquefaction facility; extensive LNG carrier construction and containment technology	None indicated
REPORTED DEVELOPMENT REQUIRED FOR CONCEPT	Scale-up of swivels, buoy and floating structure	None identified	None identified but have comparison study for qualification of concrete as secondary barrier	None indicated other than customary model test	No specific data given but proposer specified that model test would be required	Model testing using California environment	Application of LPG technology to LNG systems.
CONSTRUCTION EXPERIENCE	Steel and concrete tanks and process facilities	Drilling and production platforms, pipeline installation. Compressor modules, etc.	Supervision of building, own fleet of drill ships	IPI is a management company formed to provide contracting and other services to the chemical industry.	Experienced in LNG receiving terminals and LNG carriers	Experience in construction of LNG carriers and other ships	Construction of LPG carriers and other ships
CONSTRUCTION SITE	None indicated	None indicated, possibly west coast	Japan or Gulf Coast	Avondale Shipyard or Hitachi Zosen, Japan	Shipyard in Japan	Shipyard in Norway or license to U.S. Shipyard	Emden, W. Germany
OTHER COMPANIES ON PROPOSAL TEAM	IMODCO, General Electric, Gilstach Cryogenics	None indicated	A. A. Tec, Gastransport; McDonnell Douglas	Many as team members with Foster Wheeler as co-contractor	None indicated	None indicated	W.R. Gerich and Assoc.

TABLE G 1 - CONCLUDED

PROPOSER	GENERAL DYNAMICS QUINCY SHIPBUILDING DIVISION	A.S. HOYER ELLEFSEN	SENER/CRINAVIS	CHICAGO BRIDGE AND IRON COMPANY	DRAVO CORPORATION	A.S. HOYER ELLEFSEN	ENERGY INVESTMENT AND MANAGEMENT, LTD.
CATEGORY	Floating	Floating	Fixed and Mobile	Fixed and Mobile	Fixed and Mobile	Subsea	Natural or artificial island
DESCRIPTION OF SUBSYSTEM	Barge modules in various sizes, dual hull, spherical storage tanks, equipped with crew quarters, process and auxiliary subsystems.	Semi submersible concrete production platform with integral submerged storage cells, based on CONPROD design.	Three barge like sections joined at the site and supported by a concrete caisson(s). Based on data from a proposal for a liquefaction facility limited to 100 foot depth.	Jack up platform, gravity-stabilized steel plate structure holding large cylindrical storage tank, four required.	Prestressed concrete construction, cylindrical storage tank on compartmented hull, roof area available for facility operations, two units required.	Terminal based upon the CONDEEP concept - a concrete gravity platform with a cluster of vertical storage cells below the water surface. Tower(s) extend above surface for platform support. 250 to 550 foot water depth.	Concrete barge berthing cut into shoreline, seven barges required.
RELATED EXPERIENCE AND EQUIP. IN OPER.	Extensive experience in design and construction of LNG carriers and related subsystems.	Experience in design and construction of similar CONDEEP structures; no process experience.	Sener has an extensive background in all types of facilities, including LNG terminals; also an extensive background in marine design and construction.	Extensive design and construction of similar cryogenic storage tanks.	Extensive concrete design and construction, well supported by other team members.	H.E. has experience in design and construction of CONDEEP structures, but no experience in process, which must be obtained.	None indicated
PROPOSAL DESIGN STAGE	Well-developed concept based on similar equipment.	Preliminary for LNG, based on oil field technology development.	Very preliminary stage, all data extracted from liquefaction facility work.	Well developed for storage facilities and marine construction, process systems not addressed.	Well developed, based on prior proposal.	Proposal is preliminary and based upon technology gained from building CONDEEP structure.	Very preliminary, lacking in detail
DEVELOPMENT TO DATE ON CONCEPT	Preliminary design for terminal LNG barge has been tested.	Extensive engineering analysis and model testing, fully verified for petrochemical application.	None indicated on receiving terminal but completed test on various subsystems.	Preliminary design for terminal, storage tank has been tested.	Preliminary design concept	None indicated on receiving terminals but complete test and analyses for petrochemical application.	None indicated; concept well developed for shore-based application
REPORTED DEVELOPMENT REQUIRED FOR CONCEPT	Adaptation of concept to design specification and regulatory requirements.	Development for LNG receiving terminal application, California environment.	Model testing using California environment and carriers.	Full development of marine structure, incorporation of all operating subsystems.	None indicated (customary model testing).	Model testing using California environment. Will require development for transfer and containment.	None indicated
CONSTRUCTION EXPERIENCE	LNG carriers and other types of ship construction.	H.E. has constructed 5 CONDEEP structures and has many years experience in reinforced concrete design and construction.	Experience in construction of all type facilities including LNG.	Cryogenic storage tanks	Concrete construction, storage tanks.	H. E. has constructed 5 CONDEEP structures and has many years experience in reinforced concrete design and construction.	None indicated
CONSTRUCTION SITE	Quincy, Mass (barges) and Charleston, S.C. (spheres)	Washington or Dillingham's facility in Hawaii.	Crinavis' shipyard in Spain	Not indicated	Not indicated	Proposed U.S. west coast site	Not indicated, dependent on site selection.
OTHER COMPANIES ON PROPOSAL TEAM	None indicated	Guy F. Atkinson, Dillingham Corp. and Dow Chemical	None indicated	None indicated	Gulf Oil and Preload Engineering Company	Guy F. Atkinson, Dillingham Corporation and Dow Chemical	None indicated

APPENDIX H

LIST OF ABBREVIATIONS

ABS	American Bureau of Shipping
ALP	Articulated Loading Platform
ANSI	American National Standards Institute
BHC	British Hovercraft Company
CALM	Catenary Anchor Leg Mooring
DWP	Deepwater Port
DWT	Deadweight Ton
IEEF	Institute of Electrical and Electronic Engineers
LCA	Longitudinal Center of Area
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LVDT	Linear Variable Differential Transformer
MARAD	U.S. Maritime Administration
MLMS	Mooring Load Monitoring System
MLPS	Mooring Load Prediction System
MLWS	Mooring Load Warning System
NDBO	National Data Buoy Office of NOAA
NEL	National Engineering Laboratory of the U.K.
NSMB	Netherlands Ship Model Basin
OTC	Offshore Technology Conference
OTS	Ocean Technical Services Limited
PPC	Pumping Platform Complex
SALM	Single Anchor Leg Mooring
SALS	Single Anchor Leg System
SBS	Single Buoy System
SPM	Single Point Mooring

APPENDIX I

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